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OLDMAN RIVER DAM PROJECT

Review of Greggs & Associates Report

JUNE 1989

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Alberta Public Works, Supply and Services
Oldman River Dam Project Office
5th Floor, College Plaza
8215 - 112 Street
Edmonton, Alberta
T6G 5A9

ATTENTION: **Mr. J.W. Thiessen, P.Eng.**
Project Manager

Dear Sir:

RE: **Oldman River Dam**
Review of Report on Bedrock Structure
By Dr. R.G. Greggs, P.Geol.

We are pleased to submit herewith our review of the report entitled "Preliminary Evaluation of the Bedrock Structure - Oldman River Dam Site Area, Southern Alberta", prepared by Dr. Robert G. Greggs, P.Geol. for Mr. Cliff Wallis, President, Friends of the Oldman River, and dated February, 1989. We have carried out this review at your request because the conclusions reached by Dr. Greggs who is a Professional Geologist, are that vertical faults exist in the reservoir and at the dam site, and pose a threat to the safety of the dam structures.

To address the issues raised by Dr. Greggs, we have had the Greggs' report reviewed in detail by our Project Geologist, Dr. B.J. Sinclair, P. Geol. and the site geology staff. We have commissioned a group of expert geologists, geophysicists and engineers who have reviewed Dr. Greggs' Report. All but one of these independent experts have provided input to the project and are therefore familiar with the particular geological conditions at the dam site and in the reservoir area. A site inspection was conducted by the project geological staff and the group of experts, of the locations identified by Dr. Greggs where the vertical faults he has postulated should be evident on the surface. Our detailed comments on each of the points raised by Dr. Greggs are contained in the attached report. In addition, we have appended the individual contributions received from each of the experts. The key comments and conclusions we have reached are as follows:

1. Dr. Greggs claims that the lower reservoir and dam site areas of the Oldman River Dam Project are characterized by vertical faults which are oriented in the NE-SW, NW-SE, as well at N-S and E-W directions and which originate in the basement.

   Regional geological studies by independent investigators prior to 1985, exploratory drilling and geological mapping studies carried out by the project team in 1985 and 1986 and further drilling and geological mapping performed during construction all indicate that there are no inclined or vertical faults of any engineering significance exposed at the ground surface in the lower reservoir and dam site areas. Geological studies carried out at the dam site during construction, i.e., since 1986, have been based on numerous additional cored boreholes, as well as geological mapping of the large areas of rock exposed during excavation. These studies have been particularly detailed and have shown no evidence of Dr. Greggs' postulated faults.

The only near-vertical fractures found in the project area are joints which show no shear displacement and hence are not faults.

2. Dr. Greggs has cited borehole core evidence, e.g., slickensides, gouge, brecciation, core loss and borehole caving, as indicative of vertical faulting.

   This evidence has been misinterpreted or misunderstood. The deformation features cited are caused by horizontal shearing along the near-horizontal bedding planes. Bedding plane shearing is inconsistent with Dr. Greggs postulated vertical faulting. Bedding plane shears are characteristic of the mudrocks in the project area and at many other dam sites in similar geology in the western Canadian plains. The mechanism for the formation of such shears is a) stress relief and valley rebound caused by river downcutting, b) glacial action, and possibly (c) tectonic action originating with the Laramide orogeny. These shears have been taken into account in the design of the foundations of the dam, spillway and other structures.

3. Various other surface geological features or data have also been cited as evidence of vertical faulting, such as lineaments, seismic refraction data, landslides and scarps and water well data.

   These features and data are not credible evidence of faulting. Lineaments in the western Canada plains region usually represent joints; there is no evidence that the lineaments identified by Dr. Greggs in the project area represent faults. Seismic refraction data are generally unsuitable indicators of faults. Landslides and scarps are common mass movement features in river valleys and, in the case of the Oldman River Dam Project, do not indicate the presence of faults. The depressed water well level data cited are from a well that draws from a bedrock aquifer in the area of the buried valley north of the dam site where low ground water levels could be expected.

   Vertical faults which are inferred to exist must be proven by demonstrating strata which are offset along vertical planes. No evidence of this type has been presented by Dr. Greggs, nor has any been found by the project investigators.

4. Dr. Greggs claims that these vertical faults have originated in the basement and

have propagated upwards through the overlying sedimentary rocks. He has further postulated that recurring movement on the fault planes relating to regional stresses, earthquakes or reservoir impounding, will render the structures unsafe.

Studies of seismicity data for the project region indicate that the level of seismicity is very low and characterized by infrequent, random earthquakes of low magnitude. There is no evidence of an association between earthquake occurrence and fault movement. The probability of future earthquake-related or reservoir-induced movement on buried faults, should they exist, in the project area is very low. The probability of the same fault movement propagating upwards to the ground surface in the lower reservoir and dam site areas is virtually nil. The latter conclusion is supported by the fact that no significant faulting has occurred in the lower reservoir and dam site areas for at least 54 million years, as attested by the absence of inclined or vertical faulting in the Porcupine Hills Formation. Rocks of this formation form the bedrock foundation at the dam site. There is no reason to believe that the stresses in the rock beneath the project area are high enough to initiate movement on buried faults, should they exist. However, should earthquake-related or reservoir-induced fault movement occur at depth, the resulting ground acceleration at the dam site is not expected to exceed the ground acceleration for which the project structures have been designed.

5. A grouting program has been designed to seal the joints in the dam foundation and reduce the potential underseepage. Dr. Greggs believes that it will not be effective in the event of fault movement.

   We have concluded there are no faults. The foundation is not unusual in terms of permeability and grouting is the conventional and proven method of minimizing underseepage. It is our opinion that our grouting system will be successful in reducing potential underseepage to acceptable amounts.

In conclusion, therefore, after considering all the issues raised by Dr. Greggs, consulting with our geological, geophysical and engineering experts and reviewing these issues in the light of all the geological evidence, it is our considered opinion that there are no vertical faults beneath the lower reservoir and dam site areas which pose a threat to the safety of the Oldman River Dam structures.

Yours very truly,
UMA Engineering Ltd.

BJ Sinclair

D.B. Chalcroft, P.Eng.
Project Manager

B.J. Sinclair, Ph.D. P.Geol.
Project Geologist

OLDMAN RIVER DAM PROJECT

Review of
Greggs & Associates Report
to
Friends of the Oldman River
dated
February 1989

Prepared for
Alberta Public Works, Supply and Services

BRIAN J. SINCLAIR
B.J. Sinclair
June 23 1989

PERMIT TO PRACTICE
UMA ENGINEERING LTD.
Signature
Date June 23/89
PERMIT NUMBER: P 329
The Association of Professional Engineers, Geologists and Geophysicists of Alberta

Prepared by
UMA Engineering Ltd.
in association with
Acres International Limited
Edmonton, Alberta

JUNE 1989

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1.0 INTRODUCTION

1.1 Objectives of Report

A report entitled "Preliminary Evaluation of the Bedrock Structure - Oldman River Dam Site Area - Southern Alberta", was prepared by Dr. R.G. Greggs, P.Geol., in February 1989 for Friends of the Oldman River, Calgary, Alberta. Dr. Greggs' report states that the lower reservoir and dam site areas of the Oldman River Dam Project are traversed by vertical faults. Specifically, they are reported as:

a) NE-SW and NW-SE-oriented faults

b) E-W and N-S-oriented faults and

c) pervasive faulting.

The report by Dr. Greggs says these faults are subject to intermittent movement which will adversely affect the dam and related structures.

This report has been prepared at the request of Alberta Public Works, Supply and Services as an evaluation of the statements made by Dr. Greggs. Geological data collected on the project are presented and the statements made by Dr. Greggs regarding faults and fault movements are assessed in the light of the collected data.

1.2 Scope of Report

Section 2 summarizes key points made by Dr. Greggs.

Section 3 describes the general tectonic setting, bedrock formations, rock units and stratigraphy in the Oldman River Dam Project area. The regional geological structure, especially faulting, is discussed.

Section 4 describes the geological conditions in the dam site and reservoir areas. Emphasis is given to stratigraphic continuity, bedding plane shears, slickensides and the origins of these features.

Section 5 discusses Dr. Greggs' evidence versus the project findings regarding the presence of vertical faults. The use of lineaments, borehole core features and other data Dr. Greggs has used to infer faults are discussed.

Section 6 discusses fault movement. This section deals with the relationship between stress and faulting, engineering considerations of surface and buried faults and fault movement, as related to regional stresses, and earthquakes, reservoir impounding. Foundation grouting is also discussed.

Section 7 discusses slaking of mudstones and the design measures to control slaking.

Section 8 presents conclusions reached by project engineering geologists and geotechnical engineers.

Appendix A comprises a series of letter reports by the expert geologists, geophysicists and engineers who have participated in various aspects of the Oldman River Dam Project studies. These reports comment on Dr. Greggs' report.

Appendix B contains a report prepared by Thurber Consultants Limited to UMA Engineering Ltd. This report discusses the results of a field investigation which was directed at searching for Dr. Greggs' postulated faults.

1.3 Definition of Terms

For the purpose of this report, the term "fracture" is generally used to describe a plane of separation, parting or failure in a rock mass. If there is evidence to show significant shear or relative displacement along the plane, the fracture is called a fault. If the evidence shows only a small movement normal to the plane, the fracture is called a joint.

2.0 GREGGS' REPORT - KEY POINTS

A summary of the key points in Dr. Greggs' report is given below to facilitate the clarity and treatment of the issues raised by Dr. Greggs. Many of the points in Sections 2.1 and 2.2 have been made elsewhere by different research workers. Points in Sections 2.3 and 2.4 deal with Dr. Greggs' evidence and his inference of faults in the project area.

2.1 Basement Structure and Stress

The basement structure in the plains of Western Canada consists of an orthogonal system of persistent, vertical fractures whose dominant orientation is NE-SW and NW-SE.

This basement fracture system results in vertical faults which are subject to movement through geologic time, producing fault blocks and such geological structures as horsts and grabens.

The maximum principal stress in the basement is horizontal, and is oriented NE-SW. The minimum principal stress may be either horizontal and NW-SE oriented or it may be vertical. These stresses are pervasive and are part of a cratonic-wide stress field.

Extensional joints oriented primarily NW-SE and NE-SW, and secondarily N-S and E-W, exist throughout Alberta.

2.2 Lineaments

Lineaments mappable at the ground surface, such as linear trends in the topography and drainage, tend to reflect the basement structure. Regional photolineament studies by different research workers indicate the presence of a dominant NW-SE and NE-SW fracture system.

2.3 Evidence of Tectonic Deformation

Dr. Greggs cites typical geological features such as gouge, slickensides and brecciation, as well as loss of drill core, loss of drill water and other information as indicators of tectonic deformation. He identifies these features in the descriptions in the borehole logs from the Oldman River Dam Project.

2.4 Dr. Greggs' Inferences

Based on a) a postulated basement fracture system, b) the assumption that these fractures are vertical faults, and c) the assumption that lineaments observed by Dr. Greggs at the ground surface in the project area, represent the same vertical faults, and using various geological features observed by Dr. Greggs on the ground and in borehole core, Dr. Greggs has inferred the following:

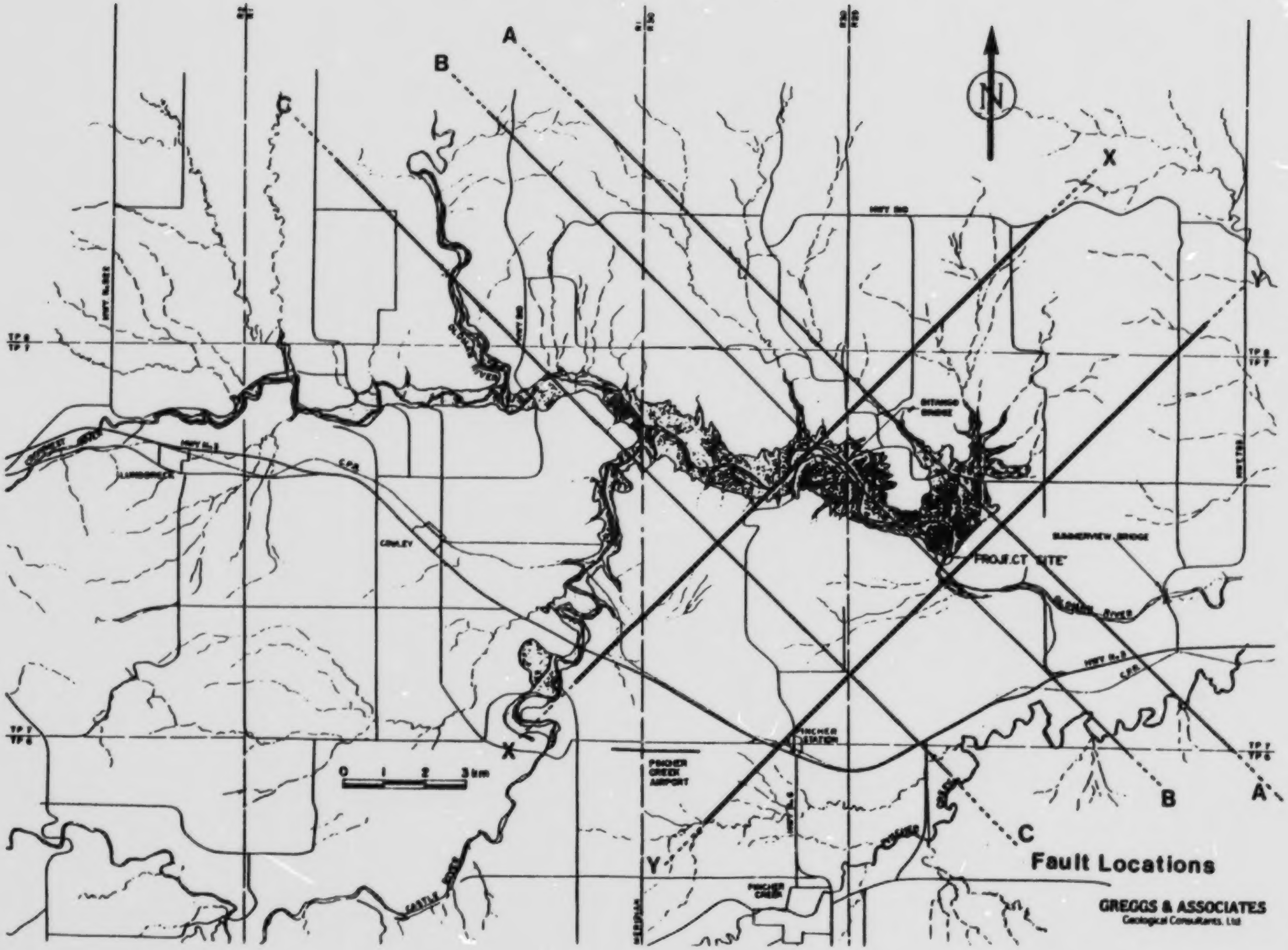
- Five vertical faults in the area of the lower reservoir and dam site. These are Faults A, B and C oriented NW-SE and Faults X and Y in the NE-SW direction. Faults B and Y pass through the dam site area.

- Other more closely-spaced NW-SE and NE-SW-oriented vertical faults, as well as N-S and E-W oriented faults, are present in the project area.

These inferred faults are shown on Plate 1.

Dr. Greggs further inferred that movement may recur along the inferred faults, causing 'jiggling' movement in the bedrock. Such movements may relate to earthquakes or may be induced by regional stresses or reservoir impounding. He states that such movement would "adversely affect the stability of any construction, such as the dam, dyke and spillway and the water retaining capabilities of the river floor and walls. The effect of these 'jiggling' movements on the dam has the potential for risk to public safety."

Finally Dr. Greggs recommends further data review, photolineament studies, field geological mapping and seismic surveys to investigate his postulated faults.


A
B
C
X
Y
N
HWY 510
HWY 785
HWY No. 3
C.P.R.
PROJECT SITE
SUMMERVIEW BRIDGE
OLDMAN RIVER
COWLEY
LUNDBRECK
PINCHER STATION
PINCHER CREEK AIRPORT
PINCHER CREEK
CASTLE RIVER
MERIDIAN
TP 8
TP 7
TP 6
0 1 2 3 km

Fault Locations

GREGGS & ASSOCIATES
Geological Consultants, Ltd

PLATE I

3.0 REGIONAL GEOLOGICAL STUDIES

3.1 Tectonic Setting and Bedrock Formations

The Oldman River Dam Project area is situated on the western limb of the NNW-trending Alberta Syncline which is east of the Rocky Mountain Foothills.

Practically all of the project area is situated in the Alberta Syncline which is a gently folded asymmetric syncline. The eastern limb dips very gently westward. The dip of the western limb varies from flat near the axis to moderately steep at the western limit.

A small area on the extreme west of the project area is in the eastern part of the folded and faulted Rocky Mountain Disturbed Belt (hereafter referred to as the Disturbed Belt). The folding and faulting in this belt, as well as the minor folding in the Alberta Syncline, is associated with the Laramide orogeny which resulted in the formation of the Rocky Mountains in this area. Deformation during the Laramide orogeny also caused the axis of the Alberta Syncline to curve from NW-trending in the area south of the dam site to N-trending north of the dam site.

The rock formations, from top to bottom, are as follows in the project area:

Formation	Approx. Age (million yr)	Area
Porcupine Hills	Paleocene (54-66)	Dam site and lower 2/3 of reservoir
Willow Creek	Late Cretaceous (66-68)	Upper 1/3 of reservoir
St. Mary River	Late Cretaceous (68-72)	Extreme upper reservoir (west limit)

Below the St. Mary River Formation, in descending order, are the Blood Reserve, the Bearpaw and the Oldman formations.

The dam site is located about 5 km west of the Alberta Syncline axis. The abutments and valley floor are composed of the Porcupine Hills Formation (Jerzykiewicz and Sweet, 1985). The Willow Creek Formation disconformably underlies the Porcupine Hills Formation at a depth of approximately 45 m below the valley floor. The dip of the rock units at the dam site is about 0.5°NE, i.e., nearly horizontal, reflecting the proximity of the dam site to the syncline axis.

The top of the Willow Creek and St. Mary River formations outcrop approximately 10 and 15 km, respectively, upstream of the dam site. The reservoir extends approximately 16 km west of the dam site. The lower part of the reservoir is located in the Porcupine Hills Formation, and most of the upper part of the reservoir is in the Willow Creek Formation. The extreme upper section of the reservoir in the Crowsnest River Valley is underlain by the St. Mary River Formation.

Proceeding from the dam site, the bedding plane dips increase gradually in the upstream direction, reaching about 12°E at the Porcupine Hills/Willow Creek contact, and about 45°E (and locally steeper), in the uppermost reservoir in the St. Mary River Formation.

3.2 Stratigraphy and Rock Types

Formations in the project area consist of claystones, siltstones and shallow overbank and deep channel sandstones. All strata are nonmarine clastic deposits and tend to be variable in the horizontal and vertical directions. The siltstones and claystones are gradational; collectively they are classed as mudrocks.

Table 1 presents general characteristics of the various rock types observed in the Porcupine Hills and Willow Creek formations at the dam site. Properties listed are considered representative of corresponding rock types observed in the lower reservoir area. Colour and weathering characteristics of the rocks found in the reservoir area vary slightly from one area to another.

TABLE 1

Rock Characteristics at Dam Site

Claystones

- grey to dark grey, occasionally black or greenish
- calcareous
- very silty; silt sizes probably comprise a higher percentage than claysizes in most claystones
- occasionally carbonaceous (correlate with black beds)
- calcrete nodules locally common
- medium plastic clay (CI), very occasionally ranging into low and high plastic clay (CL and CH) (2)
- XRD analysis of the clay-size fraction shows (3)
  - . quartz is the predominant mineral
  - . calcite, dolomite, kaolinite and mica are secondary minerals
  - . smectite and chlorite are present as trace amounts in the majority of samples
- generally show a slow rate of slaking, although some samples rated as very fast (4)
- develop a fissured structure as a result of weathering
- strength descriptions vary from very weak to strong (1)

Siltstones

- light grey to dark grey, occasionally greenish or black
- calcareous
- range from clay rich to sand rich
- occasionally carbonaceous (correlate with black beds)
- calcrete nodules locally common
- medium plastic clay (CI), commonly ranging from nonplastic, to low plastic silt or clay (ML or CL) and rarely to high plastic clay (CH) (2)
- XRD analysis of the clay size fraction shows as for claystone (3)
- commonly develop a fissured structure as a result of weathering
- sandier units often show ripple lamination structures
- strength descriptions vary from very weak to very strong (1)

Sandstones (overbank and shallow channel facies)

- light grey to dark grey, some pale brown and pale greenish grey
- generally fine grained (most grains 0.125 mm to 0.25 mm), occasionally thin, medium to coarse grained zones
- poorly graded (SP, occasionally SM) (2)
- often silt rich
- calcrete nodules occasionally present
- thin, rip-up clast conglomerates comprised of mud chips and/or carbonaceous debris occasionally present
- the average composition and roundness characteristics of the clastic components are
  - . quartz (30%), subangular to subrounded grains
  - . chert (30%), subangular to angular grains
  - . carbonate (30%), subangular to angular grains
  - . feldspar, chlorite, white mica, biotite, apatite, tourmaline, opaques, organic matter, zircon and rock fragments (10%)
- the cement components are mainly
  - . carbonate (most abundant)
  - . kaolinite
  - . silica
- very low porosity (1% to 5%)
- laminated and bedding structures common
- strength descriptions vary from moderately strong to very strong (1)

Sandstone (deep channel facies)

- light grey to grey, some pale brown and pale greenish grey
- fine, medium and coarse grained
- poor to well graded (SP and SW) (2)
- beds or rip-up clast conglomerate composed of mud chips and/or carbonaceous debris common
- occasionally conglomeratic (detrital calcrete nodules, mud balls andmud chips mostly)
- occasional detrital coal pockets (probably transported tree branches or roots)
- average composition and roundness characteristics of the clastic components and cement components same as for overbank/shallow channel facies
- very low porosity
- bedded structures common, occasionally laminated structures
- strength descriptions vary from strong to very strong (1)

(1) The system of rock description developed by the Geological Society Engineering Group Work Party (Anon (1977)) was adopted for the Oldman River Dam Project.
(2) Soils and soil properties have been classified and described according to the Unified Soil Classification System (U.S.B.R., (1974)).
(3) XRD means X-ray diffraction analysis.
(4) Slaking of mudrocks has been classified according to the system proposed by Morgenstern and Eigenbrod (1974).

At the dam site three major rock units were identified for project design purposes. The following table correlates these units to the rock formations.

Formation	Major Rock Unit	Approx. Contact Elevation (m)*
Porcupine Hills	Upper Mudrock Sequence	
		1048*
	Basal Sandstone Sequence	
		1005*
Willow Creek	Lower Mudrock Sequence	

* In valley bottom at dam centerline.

The Upper and Lower Mudrock Sequences comprise predominantly mudrocks with minor sandstone beds. Channel sandstones, which were probably deposited in a fluvio-deltaic environment, are characteristic in the Upper Mudrock Sequence. The Basal Sandstone Sequence is composed of mostly uniform sandstones in its upper and lower members; the intermediate member comprises alternating sandstone and mudrock. Bed thickness is in the order of 0.5 to 2 m in the mudrock sequences and up to 5 m or more in the Basal Sandstone Sequence.

Thin beds of black or dark grey carbonaceous claystone and siltstone occur throughout the mudrock sequences. These strata are continuous across the dam site and therefore serve as stratigraphic marker beds.

3.3 Regional Studies by Independent Investigators

3.3.1 Faulting in Disturbed Belt and Alberta Syncline

The regional structural geology in the eastern part of Disturbed Belt and the adjacent Alberta Syncline has been studied by several government and oil company geologists. Published maps showing bedrock lithology and structure have been produced by Douglas (1950, 1951), Price (1961), Okulitch and Woodsworth (1977), Irish (1967) and Bally et al (1966). None of the published map data show any faulting in the Porcupine Hills Formation which underlies the dam site and lower reservoir areas.

These maps show thrust faults along the upper reaches of the Crowsnest River in the lower Willow Creek and St. Mary River formations; this section is in the eastern part of the Disturbed Belt. The Oldman River Dam Project reservoir extends a short distance into this area.

The eastern limit of the Disturbed Belt, although not precisely located, is in the lower Willow Creek Formation or the upper St. Mary River Formation, according to regional geological maps.

The eastern part of the Disturbed Belt is characterized by thrust faulting associated with the Laramide orogeny. The faults dip mostly westward, with some dipping eastward (Price 1961) (Bossort 1957). They are more steeply dipping at the surface and curve (concave upward) with depth, eventually becoming near-horizontal. The resulting fault blocks have been rotated upward. Folding is also characteristic in this area, resulting in eastward and westward-dipping strata. The intensity of deformation increases in the westward direction. In the transition area, between the Alberta Syncline and the Disturbed Belt, i.e., the uppermost part of the project area, the deformation is relatively mild and consists mainly of folding.

The orientations and inclinations of faults found in the Disturbed Belt indicate that they resulted from a NE-SW-oriented, maximum horizontal compressive stress. This stress orientation is compatible with that of the Laramide orogeny. No vertical faults, horsts or graben structures, as described by Dr. Greggs, have been identified in any of the above studies.

3.3.2 Faulting at Depth

Bossort (1957) has addressed the question of faulting in the rock beneath the Porcupine Hills Formation, in the lower reservoir and dam site areas. Bossort states "deep-seated faulting in the foothills west of the Porcupine Hills/Willow Creek contact has no surface expression east of the contact. This faulting can be traced with reflection seismograph eastward beneath the Porcupine Hills/Willow Creek contact." He further states that surface mapping "reveals deformation in the Willow Creek and all older strata, while folding and faulting are conspicuously absent in the Porcupine Hills strata." An east-west oriented geological section, several kilometres north of the project area, shows a low angle, westward-dipping thrust fault that extends through the St. Mary River and Willow Creek formations and terminates at the Porcupine Hill/Willow Creek Formation contact. Bossort's finding that there are no faults in the Porcupine Hills Formation agrees with the studies discussed earlier.

3.3.3 Other Faults

Studies by Irish (1967) and Douglas (1951) were carried out in an area immediately southeast of the project area, where the Willow Creek Formation forms the bedrock surface. The rock formation here is stratigraphically equivalent to the Willow Creek rock underlying the dam site and lower reservoir. Although minor local anticlinal and synclinal folding was found, no faults were observed. These studies suggest there are no faults of any significance in the Willow Creek Formation below the Porcupine Hills Formation in the lower reservoir and dam site areas.

Mapping by Irish (1967) shows an area of thrust faulting known as the Monarch Fault Zone located 60 km north-east of the Oldman River dam site (20 km north-west of Lethbridge). These thrust faults occur in a rock sequence comprising, from top to bottom, the lower part of the St. Mary River Formation, the Blood Reserve Formation and the top of the Bearpaw Formation. The faulted zone is approximately 10 km in length. The thrust faults are eastward dipping and show small displacements. Some of this faulting may be associated with glaciotectonic activity, as discussed in Section 4.2.1.

Irish (1967) describes another small thrust fault about 10 km southwest of Lethbridge. It is located in the lower part of the Bearpaw Formation and the upper part of the underlying Oldman Formation.

With respect to Dr. Greggs' statement on vertical faulting in the general area of the Oldman River Dam, Savigny (1989) comments as follows:

> "Dr. Greggs (p.5, para. 2) references Russell and Landes (1940) as saying " ..... vertical faulting is thoroughly documented in this general area ....." It should be pointed out that Russell and Landes (1940) deal almost exclusively with the area approximately east of Lethbridge (113° longitude). They consider about 15 different regional structures of which only two are believed to be associated with faults.
>
> The first and closest fault to the dam site is at the City of Lethbridge where the following description is given: "Folds are broken only by normal faults, most ..... small magnitude and doubtless extending to no great depth ..... Only two are of sufficient magnitude to carry to depth." The second area of faulting is south of Medicine Hat where uncertainty is expressed as to whether off-set beds are a result of slope instability or faulting. Therefore, Dr. Greggs' reference does not appear consistent with statements by Russell and Landes (1940). Moreover, several more recent and widely referenced publications, which Dr. Greggs does not cite, show no ground surface faulting east of the Disturbed Belt in the Pincher Creek - Fort McLeod area (Douglas, 1950; Irish, 1967; Price, 1966; Gordy et al., 1977)."

4.0 DAM SITE AND RESERVOIR GEOLOGICAL STUDIES

4.1 Investigations Performed

Geological studies in the reservoir and dam site areas, relating to claims made by Dr. Greggs, are summarized below.

Table 2 summarizes the amounts of exploratory work done in the dam site and reservoir areas, exclusive of laboratory testing, and construction materials exploration.

TABLE 2

Project Investigations

	Dam Site Area		Reservoir Area	
	(No.)	(m)	(No.)	(m)
Cored boreholes	86	3350	39	1180
Overburden drilling	128	1230	42	930
Exploratory shafts	6	168	2	72
Test tunnel	1	100	-	-
Test pits, trenches and surface exposures	93	-	-	-
Refraction seismic surveys	-	12,000	-	-
Downhole geophysics	37	2400	-	-

4.1.1 Dam Site Area

Initial Investigations

Studies began in April 1985. Emphasis was given to establishing the geological and geotechnical conditions at the dam site by means of the following exploratory tools:

- literature review
- geological mapping
- mapping of rock exposed in test trenches
- exploratory drilling, sampling and logging

- large diameter exploratory shafts, sampling and logging
- water pressure testing, to measure permeability
- downhole geophysical logging, including gamma-gamma and neutron methods, to assist in delineating stratigraphy
- refraction seismic, to determine depth of overburden
- laboratory testing

In August 1985, a seismicity study was performed in which the maximum credible earthquake and its associated ground motion at the dam site, and the potential for reservoir-induced seismicity were assessed. A microseismic monitoring network was also established. In April 1989, the seismicity study was brought up to date to take into account the additional seismic record available and to include the results of the microseismic study.

From October 1985 to January 1986, a test tunnel was excavated on the left abutment near the site of the downstream diversion tunnel portal. This tunnel geology was mapped in detail and the tunnel was instrumented to determine rock movement in response to excavation.

During 1986 and 1987, the field exploration program continued with additional drilling and coring, excavation and logging of exploratory shafts, laboratory testing and further detailed geological mapping.

Investigations During Construction

During the period, October, 1986 to August, 1987, the twin 900 m long diversion tunnels and portals were excavated in the left abutment. The tunnels, as well as the inlet and outlet portals, were geologically mapped in detail and instrumented.

As construction proceeded from late 1986 to the present, other excavated areas were geologically mapped, including most of the 450 m long dam core trench and the spillway headworks, chute and flip bucket (total length accross the river valley and into the uplands - 800 m). The geology exposed in the drainage tunnels into each of the abutments (total length - 1500 m) was also mapped.

As is normally done in dam engineering, geological and geotechnical studies at the Oldman River Dam Project developed over time and have become very detailed following the initial studies in 1985 and as more rock was exposed during construction.

The area of rock which has been excavated and geologically mapped and the number of boreholes which have been cored and logged in the dam site area are now very considerable. The amount of surface and subsurface geological data collected and analysed to date is very large. Study of these data has led to a comprehensive understanding of the geological conditions in the project area. Furthermore, numerous individuals trained in engineering geology and geotechnical engineering and from several consulting engineering companies have been involved in the work.

4.1.2 Reservoir Area

Studies of the reservoir area began in 1985 with an office air photo study, followed by a ground reconnaissance. Preliminary appraisal of the structural geology was also made at this time. Following this, a detailed geological mapping program around the reservoir rim was performed. Bedrock structures -- bedding, joints and shears -- were studied closely. Considerable exploratory drilling, coring and sampling were done. Large-diameter exploratory shafts were excavated, sampled and logged.

4.2 Results of Investigations

4.2.1 Relative Displacement Features

Faults

Design requirements at dam sites necessitate detailed geological mapping. At the Oldman River Dam Project, this mapping continued into the construction phase. Special attention was paid to the lateral and vertical continuity of the rock strata. The presence of thin black carbonaceous marker beds enabled determination of strata continuity over the upstream to downstream length of the dam site and across the river valley from one side to the another. A large number of excavated rock exposures were observed and mapped; these included road cuts, tunnel and portal excavations and the dam core trench. The continuity of all strata including the marker beds, was closely examined. Many boreholes were drilled and logged on both abutments and in the river bed. The results of the detailed mapping of the strata and the analysis of extensive borehole data, including the preparation of geological cross-sections, showed no evidence of inclined or vertical faults of any significance to the project engineering design.

Near-horizontal bedding plane shears which are common to most mudrock sequences in river valleys in the western Canadian plains were, however, encountered. These features which usually originate by mechanisms other than tectonic faulting are discussed in detail below.

Similarly, during the mapping in the lower reservoir area, no inclined or vertical faults of any engineering significance were discovered. Faults, if existing, would be apparent in the essentially continuous rock outcrops along the steep valley walls.

During field mapping, minor faults were observed northeast of Lundbreck in the uppermost reservoir area along the Crowsnest River valley. Here the reservoir overlies the eastern part of the Disturbed Belt where minor faults were anticipated.

Bedding Plane Shears

During field investigations, mudrocks were seen to be characterized by frequent bedding plane shears. These are planes of weakness along which some relative displacement has occurred. They are usually parallel to the near-horizontal bedding planes and are characterized by the presence of such shear indicators as brecciation, silt and clay gouge, small angular rock fragments, and occasional slickensides. The magnitude of the relative displacement along a particular bedding plane shear is usually undetectable, due to the apparent absence of stratigraphic offset; these features are, nevertheless, inferred to be near-horizontal shears based on the shear indicators listed.

Bedding plane shears may technically be termed "faults" because they have developed through interbed shearing displacement. However, the term "bedding plane shear" is preferred in engineering studies. The reason for this is that bedding plane shears usually originate through non-tectonic forces and are common in areas which are not tectonically active. They are accommodated routinely in design of foundations in mudrock sequences.

Extensive studies of bedding plane shears were performed at the Oldman River dam site. Their observed characteristics are as follows:

- They usually occur along contacts between relatively strong and weak rocks, e.g., sandstone and claystone.
- They parallel bedding, and hence, are usually near-horizontal in the flat-lying mudrocks.
- They may occur as single shear planes, groups of closely-spaced parallel shear planes, or as brecciated zones, i.e., numerous intersecting fracture planes.
- Single shear planes are usually less than 2 mm thick and occasionally up to 10 mm thick. Groups of shear planes or brecciated zones can have an aggregate thickness of up to 75 mm. Thickness is highly variable.
- Thin shear planes often contain fillings of silt and clay gouge, whereas

thicker ones may contain small angular rock fragments and gouge.

- They are commonly associated with the thin, dark carbonaceous marker beds.

- They are commonly continuous for distances of up to hundreds of metres.

- Depending on the thickness of the mudrock unit, secondary, curved shear planes dipping at angles up to 50° may occasionally splay off the main bedding plane shear and terminate. These shears are usually less than 1 m long.

Besides the dam site area, bedding plane shears were frequently found in rocks around the reservoir rim.

Bedding plane shears are common features in interbedded claystone and siltstone sedimentary rock sequences in the plains region of Western Canada and elsewhere. Morgenstern (1988) describes these features, their origin, and their impact on foundation shear strength. According to Morgenstern, dam foundations possessing features similar to bedding plane shears observed at the Oldman River Dam Project include:

- Gardiner Dam, Saskatchewan (constructed)
- Nipawin Dam, Saskatchewan (constructed)
- W.A.C. Bennett Dam, British Columbia (constructed)
- Peace Canyon Dam, British Columbia (constructed)
- Site C Dam Project, British Columbia (preliminary design stage)
- Dunvegan Dam, Alberta (feasibility design stage)

Davison (1989) and UMA-SNC (1979) have also observed bedding plane shears at:

- Forty Mile Coulee Dams, Alberta (constructed)
- Dickson Dam, Alberta (constructed)

Matheson and Thomson (1973) describe bedding plane shears found in two bridge pier foundations in Edmonton, Alberta. Ferguson (1967) and Ferguson and Hamel (1981) describe similar features, and other deformation features, in dam and lock foundations in flat-lying sedimentary rock in eastern United States.

Morgenstern (1988) and others attribute the bedding plane shears to the following general mechanisms:

- valley rebound
- glaciotectonic activity
- tectonic activity

To some extent, each of these mechanisms has probably contributed to the formation of bedding plane shears in the mudrocks at the Oldman River Dam Project. Valley rebound is likely to have caused most of the shearing. Valley rebound is a stress relief phenomenon that is caused by river downcutting. As river downcutting occurs, the existing horizontal stresses in the valley walls are relieved and individual beds move differentially toward the valley center. Below the valley floor, the reduction in vertical stresses results in uplifting and arching of the beds. As a consequence, shearing occurs along bed surfaces, as well as occasionally obliquely across beds. Valley rebound phenomena can extend to considerable depth below the valley bottom and laterally to considerable distance into the valley slopes.

The glaciotectonic mechanism is also likely to have contributed to horizontal shearing. As in many parts of Canada, the project area was glaciated several times and hence was subjected to the effects of repeated ice movement. The shearing forces imparted to the upper bedrock can be large and can exceed the strength of weaker siltstone and claystone beds. The depth of rock affected by such shear action is seldom known, but it can be several metres. Stalker (1962) has commented on the effects of glaciation on near-surface bedrock. He describes large bedrock masses embedded in intertill deposits in southern Alberta.

Tectonic forces originating during the Laramide orogeny have probably also had some effect. Proximity of the Rocky Mountains to the dam site and the fact the Alberta Syncline is gently folded, suggest that the effects of these tectonic forces probably extended as far east as the Oldman River Dam Project area. These forces were compressive, horizontal and NE-SW oriented. At the dam site, the degree of folding was slight, but may have been enough to cause some shear movement between competent and incompetent strata. The fact that bedding plane shears occur in non-tectonic areas such as Eastern Alberta and Saskatchewan indicates that tectonic activity is not required for their formation.

Each of these shear mechanisms result in differential movement along relatively weak, horizontal bedding planes in flat-lying mudrock sequences. This, in turn, results in such features as brecciated rock, slickensides and gouge.

The effect of bedding plane shears has been taken into account in the design of the Oldman River dam, spillway and other structures.

Zones of Slickensides

In some claystone beds, especially the carbonaceous claystones, in the dam and spillway foundation, zones of slickensides were identified during exploratory drilling and core logging. These zones contain an unusual number of multidirectional, slickensided planes. They are often discontinuous across the borehole core, as indicated by the fact that the cores usually remained intact upon removal from the core barrel.

Zones of slickensided planes tend to be characteristic of particular beds. They can usually be correlated from one borehole to another. Although relative displacement is usually not directly observable, small near-horizontal shear movement was likely responsible for their formation.

Similar zones of slickensided planes were encountered in borehole cores obtained from drilling in the reservoir area. They were also observed in the bedrock at Forty Mile Coulee dam site south of Bow Island, Alberta (Davison, 1989).

Several mechanisms are possible for the formation of the zones of slickensiding. Valley rebound appears to be the most likely cause, but tectonic or glaciotectonic activity may also have contributed. Alternatively, the slickensided planes may have resulted from shearing of the sediments during sedimentation or subsequently while they were in the plastic state.

Shear Features

In the spillway flip bucket area, near the valley wall on the right abutment, a normal fault striking N52°W and dipping 50°SW was encountered. It extended from elevation 1075 m down to elevation 1066 m, where it curved into a horizontal bedding plane. In its upper part, an offset of approximately 35 cm was measured. This offset progressively decreased to zero at elevation 1066 m. Clay filling was observed in the fault. In the test tunnel, occasional joints with approximately the same orientation as the above fault showed minor offsets of a few centimetres.

These small displacements at the dam site are considered to have resulted from the same processes that caused bedding plane shears and zones of slickensiding. As described earlier, the bedding plane shears were observed to occasionally terminate in inclined splays.

In the base of a coulee on the right bank, at about elevation 1079 m, a "pop-up" was observed. Pop-ups are small local flexures in the near surface strata, and are caused by relief of vertical stresses and buckling. They are common geological features and are described by White et al (1973) and Gough and Gough (1987). At the Oldman River dam site, the pop-up flexure is about 20 m wide, and its axis trends ESE. A small thrust fault striking E-W and dipping 45°S and showing a minor offset, was observed in the fold. This fault becomes horizontal with depth, merging into one of the bedding plane shears.

Pop-ups are related to stress relief. In river valleys, the river erosion causes a reduction of vertical stress relative to horizontal stress and ultimately overstressing and buckling of thinner near-surface strata.

Planes showing minor relative displacements have also been observed locally adjacent to sandstone channels in the Upper Mudrock Sequence. These are considered ancient slump features caused by deformation during the process of sedimentation.

4.2.2 Jointing

Mapping of the distribution and characteristics of the joints was performed at the dam site and at several locations in the reservoir area. At the dam site, two primary and two secondary sets of joints were found; their strike, dip and other characteristics are given in Table 3. The N-S and E-W-trending sets are most common. There is considerable variation of mean orientation across the dam site. Sets 3 and 4 are locally non-existent.

In the reservoir area, most joints are near-vertical. In the lower reservoir area the N-S and E-W-trending sets are predominant in the Porcupine Hills Formation. Several subsidiary sets were also noted. In the lower part of the Porcupine Hills Formation and in the upper part of the Willow Creek Formation, 10 to 12 km upstream of the dam site, the predominant joints are approximately parallel and normal to the strike of the bedding, i.e., NNW and WSW. Several subsidiary sets also exist, including N-S and E-W-trending sets. In the lower part of the Willow Creek Formation and upper part of the St. Mary River Formation, the N-S joint set is common, as is a NE-SW set. Locally, joint orientations and frequencies are variable. Joints tend to be moderately spaced in mudrocks and widely to extremely widely spaced in sandstones.

Joint observations and mapping have indicated no shear displacement along near-vertical joint planes at the dam site. Locally, in some areas where near-vertical joints intersect near-horizontal bedding plane shears, some fragmented rock can be seen; this is considered a feather-edge effect, resulting from bedding plane shear movement across pre-existing near-vertical joints. This is encountered in the brittle sandstones. In the sandstones in the uppermost abutments, stress relief in closely-spaced near-vertical joints has caused the rock to locally fragment and appear faulted. Close inspection, however, indicates no shear offsets and hence no faulting.

TABLE 3

Jointing in Dam Site Area*

Set	Strike/Dip	Characteristics
1 (primary)	S88°E/80°S to 90° (E-W set)	Dominant set, trends N of E on upstream side, and S of E on downstream side of dam axis; continuity > 10 m, spacing 1-2 m; found in all rock units; strongly developed in abutments.
2 (primary)	N12°E/80°E to 80°W (N-S set)	Trends ± 20° of N; these joints terminate on set 1, less continuous than set 1; found in all rock units; strongly developed in valley floor.
3 (secondary)	S44°E/60°NE to 90° to 60°SW	Found mainly in sandstones; sub-parallels the Alberta Syncline axis.
4 (secondary)	N42°E/70°SE to 90°	Found mainly in sandstones.

* Note: Bedding plane joints excluded.

5.0 EVIDENCE REGARDING FAULT EXISTENCE

5.1. Introduction

Dr. Greggs infers existence of the following vertical faults in the lower reservoir and dam site areas:

- five faults A, B, C, X and Y oriented in the NW-SE and NE-SW directions,
- other more closely-spaced faults in the same directions and
- faulting in the N-S and E-W directions.

We believe the rationale used by Dr. Greggs to arrive at such conclusions is as follows. Dr. Greggs assumes the presence of a NW-SE and NE-SW-oriented vertical fracture pattern in the basement. He assumes that these fractures are faults which are subject to recurring movement. Dr. Greggs says that lineaments at the ground surface reflect geological structure in the basement. Then, at the ground surface, in the lower reservoir and dam site areas, Dr. Greggs identifies what he believes to be lineaments and also various geological features which he believes indicate vertical faulting. Thus, Dr. Greggs' evidence to suggest faults appear to be lineaments and various geological fractures; the latter include the following:

- Borehole core features, such as brecciation, gouge, shear surfaces, slickensides, etc.
- Degree of fracturing in the valley floor.
- Indications from limited seismic refraction data.
- Reports of recent landslides along scarps.
- Data from water wells.
- Local outcrop observations.

Dr. Greggs' evidence for faulting and the views of the project engineering geologists and geotechnical engineers are discussed in the following sections.

5.2 Process of Inference

Depending on the objectives of a particular geological investigation, e.g., prospecting and exploring for ore bodies and oil deposits, or determination of geological and geotechnical foundation conditions for civil engineering works, the processes of inference and deduction are frequently used. This approach is necessary because the objects of investigation are often not directly observable. For instance, inference is often used in preliminary studies to identify the possible or probable, presence or absence, of certain features hidden from direct observation. Inference may be based on a variety of indicators. Each can have a certain degree of reliability; the more reliable the indicators, the greater the strength of the inference. Hence different types of data are collected and interpreted, and inferences are drawn from them.

Dr. Greggs has suggested specific fault locations and pervasive faulting at the Oldman River Dam Project, based almost exclusively on inference. Yet inferences are not proof; they remain unproven until verified. Proven evidence of vertical faulting requires clear demonstration of vertical faults from visible stratigraphic offsets, reliable seismic data, detailed borehole data, etc. No such evidence for Dr. Greggs' postulated faults was found during the initial investigations at the dam site and reservoir or during the subsequent extensive geological mapping and drilling performed during construction.

5.3 Lineaments

5.3.1 Description

A considerable volume of literature has been written on the subject of lineaments. It is not intended to elaborate here, but a recent state-of-the-art paper by Mollard (1988) on the subject of lineaments, as observed in the western Canadian plains, is relevant to the claims made by Dr. Greggs on the Oldman River Dam Project.

By way of description of lineaments, the following is taken from Mollard (1988):

> "Fracture lineaments are composite linear features mapped [on the ground surface] from airphotos and space imagery .... Typically fracture lineaments are narrow and straight, and occur in a hierarchy of orders: global, regional, and local. Fracture lineaments form networks of intersecting linear features grouped in subparallel arrays called sets. Two or more sets displaying consistent angular relationships over large areas are called systems. One to eight preferentially developed sets may appear in a region. Strongly preferred related sets, called pairsets, commonly intersect at approximately 90°. On the western Canadian plains, four sets regularly consisting of double suborthogonal systems, are common. Such attributes are not only characteristic of fracture lineaments but also of global, regional, and local joint and fault systems in the Earth's upper crust (Hodgson 1961, 1977).
>
> Fracture lineament patterns [on the ground surface] appear to be linked with crustal movements that reflect fracture systems and structures in the underlying rocks. Resulting genetic and geometric relationships have significant implications in a wide variety of resource exploration, development, and management applications."

5.3.2 Basement Structure and Lineaments

It is recognized that a comprehensive study of surface lineaments may reflect deep geological structure at a site, whether it is basement structure, or structures at different levels in sedimentary rocks above the basement. Such study requires detailed examination and comparison of data shown on geological maps, Landsat imagery and air photos on different scales and topographic maps, as well as geophysical evidence interpreted from aeromagnetic maps, gravity maps, seismic profiles, etc.

Correlation between lineaments and surface and near-surface, faults and joint zones demands detailed examination of a considerable amount of surface and subsurface geological data, as well as geophysical data. Without making detailed studies at a given site, lineaments observed at the surface may represent joints, or faults. Because most surface lineaments represent joint trends, proof is required that significant stratigraphic offsets have occurred along vertical planes before affirming that the surface lineaments overlie vertical faults.

5.4 Dr. Greggs' Evidence Versus Project Findings

5.4.1 Inferences from Lineaments

Fault A in Dr. Greggs' report is identified as a master fault at the Oldman River Dam Project. It is identified on the basis of the extension of the Bridger Lineament in Colorado, some 1200 km away from the Oldman River Dam Project.

Our review of information regarding the Bridger Lineament indicates the following points:

Figure 2 of Dr. Greggs' report shows the Bridger Lineament is one of several NW-SE-oriented lineaments shown in a paper by Maughan and Perry (1986). The Maughan and Perry paper states "the lineaments shown in Figure 2 are composites of shorter linear trends evident on the lithofacies and isopach maps of each of the stratigraphic intervals on the U.S. Geological Survey paleotectonic maps of the Mississipian -Triassic Systems." According to Maughan and Perry, some of the lineaments are "coincident with faults in the Precambrian rocks and seem to be related to them...." They also state "recurrent movements along some of these lineaments are indicated by their coincidence with both older Precambrian faults and younger Laramide faults."

On their map Maughan and Perry identify the Bridger Lineament, not the "Bridger Fault", as Dr. Greggs has done. They do so probably because the feature is not a proven fault. Nowhere in their paper is there a reference to the Bridger Fault. The recurrent movement they refer to occurred in the Middle Phanerozoic or earlier, i.e., the distant geological past.

Figure 2 of Dr. Greggs' report shows the Bridger Lineament extending only as far north as southern Montana. Figure 4 of Maughan and Perry (1986) indicates that the Bridger Lineament, as expressed at the ground surface, is confined to the state of Wyoming, i.e., its surface continuity is limited. If the Bridger Lineament were indeed a fault, it is highly improbable that it extends to the Oldman River Dam Project area.

Figure 3 in Dr. Greggs' report, taken from Downey et al (1987), shows the lineaments in the same general area as for Figure 2, but mapped from Landsat imagery. There is little similarity in the set directions, number of sets, and furthermore, continuity of lineaments shown in Figures 2 and 3 do not match. The Bridger Lineament is not shown on Figure 3, nor is it referred to in the paper by Downey et al (1987). This casts further doubt on the use of these lineament maps to infer faults hundreds of kilometres to the northwest in southern Alberta.

Dr. Greggs also uses lineaments to infer the existence of Faults B, C and X and Y as follows:

Fault	Lineament Evidence Given by Dr. Greggs.
B	"geomorphology of the river and its banks."
C	"topographic and geomorphologic features".
X	"local trend of the Oldman River (IFIV) (incised fault-induced valley), strong geomorphologic trends."
Y	"local trend of the Oldman River (IFIV), geomorphologic trends."

Dr. Greggs also mentions "traces of sections of the [fault] blocks..... show clearly on the topographic maps," but does not elaborate.

Based on our understanding of the application of lineaments to indicate faults, and based on extensive project field mapping studies over several years, we conclude that there is no evidence to suggest that any of Dr. Greggs' lineaments actually indicate surface or near-surface faults. Dr. Greggs shows little or no geological or geophysical data to verify his inferred faults. Evidence of vertical faulting, i.e., stratigraphic offsets, if it did exist, would be readily apparent in the rock outcrops along the river banks and at other locations.

5.4.2 Data from Borehole Cores

Dr. Greggs lists typical indicators of tectonic deformation in a rock mass as follows:

- fractures.
- slickensides.
- faults.
- brecciation.
- fault gouge.
- stylolites.
- hydrothermal minerals.
- poor core recovery in boreholes.
- loss of drill water and production of water in boreholes.
- borehole caving.

He then states "shear fractures, slickensides, brecciation and offset beds indicate movement - all of these geological features have been reported in the Oldman River dam site test cores." Excerpts from several borehole logs are given in Dr. Greggs' report which show several of the above geological features. This information is then cited as evidence that faults exist in the project area.

We consider that all such geological features described in the borehole logs are indicators of shearing along near-horizontal bedding planes. They are not indicators of vertical faulting as suggested by Dr. Greggs. The causes of the horizontal bedding plane shearing observed at the Oldman River Dam Project are described in Section 4.2.1. Our explanation of the specific features noted by Dr. Greggs in the borehole logs is given below.

Slickensides, gouge and brecciation features were commonly encountered in bedding plane shears at many stratigraphic horizons encountered in the boreholes. Joint fractures were occasionally observed in association with bedding plane shears. The term "fault" was used in a borehole log (BH-85-107) from the reservoir to describe a minor offset associated with a bedding plane shear between a sandstone and a claystone. Core recovery was generally excellent, except locally where drilling technique or equipment was not optimum, or the soft bedding plane shear fillings were washed out by the drill wash water.

The loss of drill wash water is not unusual in bedrock abutments containing open joints and where the ground water table is below the bedrock surface. Similarly, local artesian groundwater conditions account for some boreholes that encountered water inflow. Local borehole caving is not unusual in mudrock that has undergone horizontal shearing at several stratigraphic levels. Finally, as far as can be determined from the logs, no mention has been made of hydrothermal minerals and stylolites.

Dr. Greggs refers to drill-induced fractures identified in the borehole logs and suggests they are natural fractures, the implication being that the project investigators underestimated fractures in the bedrock. In exploratory drilling investigations of the type performed at the Oldman River Dam Project where vertical drilling intercepted near-horizontal and relatively weakly bonded bedding planes, it is not unusual to encounter frequent drill-induced fractures in the drill core, mostly normal to the core axis, but also at other inclinations. These fractures are caused by the torsion applied at each bedding plane by the drill bit. Although drilling technique can cause drill-induced fractures, an experienced driller can minimize them. Engineering geologists responsible for core logging were very experienced; they were fully aware and able to distinguish between drill-induced and natural fractures.

Using records of drill core information, Dr. Greggs appears to have misinterpreted or misunderstood the data and wrongly concluded that the project area is characterized by "pervasive vertical faulting".

The report titled "Oldman River Dam - Preliminary Engineering Report", issued by UMA/Acres in March 1986 and referenced by Dr. Greggs, addressed the issue of bedding plane shears and slickensides as they were understood at that time. Both the main report and Appendix D describe these features and their diagnostic indicators -- brecciation, fillings of silty/clay gouge and fragmented rock. Probable mechanisms for the formation of these features are presented in that report, and are essentially the same as those discussed in Section 4.2.1.

5.5 Other Evidence

5.5.1 Degree of Fracturing

Dr. Greggs states that "the river floor is extensively fractured" and implies that the degree of fracturing indicates the proximity of faults.

It is commonly known that fractures are not necessarily faults; in fact, the great majority of fractures in any rock mass are joints and not faults. all the evidence available indicates that fractures at the Oldman River dam site are in fact, joints and not faults. The joint characteristics at the Oldman River dam site are similar to those in all river valleys formed in soft sedimentary rocks and are a function of near-surface weathering processes and stress relief during valley formation.

5.5.2 Seismic Refraction Studies

Dr. Greggs refers to refraction seismic lines showing suggestions of faults.

Seismic refraction techniques were utilized in 1985 to determine overburden thickness at the Oldman River dam site. In our opinion, seismic refraction is rarely used to indicate the presence of faults at dam sites; traditionally, in foundation engineering studies at dam sites, these techniques are used to differentiate overburden which has a low seismic velocity, from bedrock which has a markedly higher velocity. Seismic reflection techniques on the other hand, are better suited to discovery of faults and other structures, as is more commonly done in oil exploration.

In reviewing Dr. Greggs' report, Wolofsky (1989) states:

> "For seismic refraction to suggest the presence of a vertical fault, the fault would have to be characterized by an exceptionally wide low-velocity zone, or to have markedly displaced the bedrock surface. Dr. Greggs does not suggest that either of these phenomena can be read from the seismic refraction surveys. He does not state in what manner the survey results support his contentions."

We conclude that refraction seismic data do not provide reliable indicators of the existence of faults at the Oldman River Dam Project site.

5.5.3 Landslides and Scarps

Dr. Greggs suggests landslides and linear scarps along the Oldman River valley are evidence for Faults C and X.

In our understanding, mass movements along valleys formed in soft, subhorizontally bedded sedimentary rock are seldom indicators of faults. Instead they are often part of the normal processes of valley evolution. Although faults can, on occasion, contribute to valley slope failures, there is no evidence to suggest the slope failures mentioned by Dr. Greggs were caused by faults.

5.5.4 Water Wells

Referring to evidence for Fault A, Dr. Greggs states that "data from the Gifford wells support the fault extension" . He does not elaborate on what data, or why the data indicate Fault A.

We think that Dr. Greggs may be suggesting that the low ground water levels known to exist in the Gifford well indicates fault presence. This is very unlikely at the Gifford well. Low ground water levels occur in this well because the well is located in the bedrock in the buried valley to the north of the dam site. Our investigations show that this valley is filled with impervious glacial till deposits. The ground water table is down near the relatively deep bedrock surface; this explains the depressed water table.

5.5.5 Outcrop Observations

Dr. Greggs refers to unspecified outcrop observations indicating Fault C.

In our view, suggestions of faults are normally supported by evidence of observed stratigraphic offsets of rock strata; however, no observed offsets are reported by Dr. Greggs.

5.6 Project Conclusions

As faults are the geological structure that could have the greatest effect on dam design, a major effort was made by engineering geologists during the early stages of dam site investigations to locate and examine any faults that may exist. It is not unusual to find faults at dam sites since rivers are often fault controlled. The Oldman River dam site investigations were carried out by experienced engineering geologists who were fully aware of the significance of faults to the design and who used all available methods to locate any faults that might exist at the dam site.

5.6.1 Absence of Vertical Faulting

Geological studies performed by the project team in the exploratory stages of the project in 1985 have indicated no evidence of inclined or vertical faults of any engineering significance in the reservoir and dam site area. Detailed geological studies at the dam site during construction, i.e., from 1986 to present, have been based on numerous cored boreholes and large areas of rock exposed by excavation; these studies have led to the same conclusions.

Two faults, Faults B and Y, alleged to exist by Dr. Greggs, pass through the dam site area and would certainly have been discovered in the past four years of work at the site. Faults marked A, C and X, if they exist, intersect the Oldman and Castle rivers in several places and would be exposed to view; the reservoir rim geological mapping did not find any evidence of these faults.

The conclusion of no inclined or vertical faulting is supported by the results of regional geological mapping by geologists working independently in the last 30 years; they indicate no faulting in the Porcupine Hills Formation east of the Disturbed Belt. These conclusions are also supported by a recent inspection (April 1989) of the alleged fault locations, discussed below.

Minor faults encountered in the uppermost end of the reservoir along the Crowsnest River valley are located in the Disturbed Belt. This faulting is described in the literature and was known to project investigators in the early stages of the investigations. Faults encountered in that area are not considered significant to the design of the project structures.

5.6.2 Evidence of Tectonic Deformation

As explained in Section 5.4.2., we believe Dr. Greggs has misinterpreted or misunderstood borehole core descriptions, evidence which he believes indicates pervasive vertical faulting. The borehole core data instead describe effects of horizontal shearing resulting largely from river downcutting/valley rebound/stress relief mechanisms and possibly Laramide orogenic activity. These features described are common in most valleys in flat-lying mudrocks in the western Canadian plains, including valleys far removed from the effects of the Laramide orogeny.

5.6.3 Quality of Dr. Greggs' Evidence

The amount and reliability of information Dr. Greggs used to infer vertical faults is limited and speculative. Hence his claim that the rocks in the lower reservoir and dam site areas are pervasively faulted lacks credibility. Regional mapping by independent geologists has been ignored. Dr. Greggs' lineament and fault mapping lacks correlation with surface and subsurface geological data. Borehole core evidence has been misinterpreted. The effects of river downcutting, stress relief and valley rebound have not been considered. Scattered bits of data from refraction seismic lines, water wells, landslides and river trends have been put forth as evidence of faulting. Conclusive evidence required to prove faulting, i.e., stratigraphic offsets, has not been provided.

5.6.4 Search for Dr. Greggs' Faults

In April, 1989 a reconnaissance was performed at the locations where Dr. Greggs' postulated Faults A, B, C, X and Y should be visible on exposed rock outcrops. Many of the locations inspected were along valley walls bordering the Oldman River where outcrops of the near-horizontal stratified rocks could be seen in cliffs. The details of this inspection are presented in Appendix B. No evidence of faulting was found during this reconnaissance.

Subsequently, a group of expert geologists, geophysicists and engineers associated with the Oldman River Dam Project visited the same areas and examined some of the borehole cores referred to in Dr. Greggs' report. Again no evidence of faulting was observed, as stated in their letter reports reproduced in Appendix A.

6.0 FAULT MOVEMENT

6.1 Introduction

Dr. Greggs states that "this regmatic fracture pattern results in vertical bounding faults to produce a mosaic of horsts and grabens which exhibit reversals of vertical movement throughout geological time."

He further states that "Vertical basement faults are subject to intermittent movements, as a consequence of natural tectonic flux. Earthquakes, as commonly understood, are not necessary to cause bedrock instability. In the Oldman dam area such movements would adversely affect the stability of any construction, such as the dam, dyke and spillway and the water retaining capabilities of the river floor and walls. The effect of these 'jiggling' movements on the dam has the potential for risk to public safety."

Dr. Greggs goes on to imply that fault movements may be earthquake-related or result from regional stress applications or the effects of reservoir impounding. The following sections discuss fault movement and also rock stress as related to faulting.

6.2 Faults and Rock Stresses

The geometry of fault systems are a function of the original stress conditions at the time of rock failure. For definition purposes, Table 4 summarizes the types of faults and their typical characteristics, which would result from certain stress conditions. Knowledge of fault characteristics can therefore indicate the original stress direction and relative magnitudes of stress.

Dr. Greggs postulates vertical fault planes and horst and graben structures. These types of structures usually result during normal or gravity faulting, wherein the movement is dip slip.

TABLE 4

Fault Characteristics

Case	*Stress Directions and Relative Magnitude	Resulting Type of Fault	Typical Dip of Fault Plane	Typical Fault Movement
1	$S_{Hmax}>S_{Hmin}>S_V$	Thrust	15-45°	dip slip, hanging wall upward
2	$S_V>S_{Hmax}>S_{Hmin}$	Normal (Gravity)	45-75°	dip slip, hanging wall downward
3	$S_{Hmax}>S_V>S_{Hmin}$	Transcurrent (Strike-slip)	vertical	strike slip

* S_{Hmax}, S_{Hmin} and S_V are the maximum horizontal stress, minimum horizontal stress and vertical stress, respectively. It is commonly assumed that these stresses represent the principal stresses.

Woodland and Bell (1988) have studied the rock stresses from 'mini-frac' testing data in the Western Canadian Basin. They conclude the following:

1) beneath much of the Alberta Plains, at depths between 750 and 3000 m, the stress regime is probably $S_V > S_{Hmax} > S_{Hmin}$, and

2) that beneath the Foothills and some adjacent areas, between depths of 1000 and 5000 m, the stress regime may be $S_{Hmax} > S_V > S_{Hmin}$ or even $S_{Hmax} > S_{Hmin} > S_V$.

Regarding stress magnitudes and relative stress values, Gough (1989) reports "the greater horizontal stress, S_H, lies in a range from slightly greater than to slightly less than the vertical stress, S_V, throughout the sedimentary basin (Woodland and Bell, in press, 1989)." and "that in the rock generally, the stress levels are low ....."

Dr. Greggs states that "well documented regional cratonic stresses are of sufficient magnitude to cause breakouts in well boreholes;" In contrast, it has been shown (Gough and Bell, 1981, 1982) that the presence of a vertical borehole in a field of unequal horizontal stresses can cause local concentration of stress around the borehole sufficient to initiate spalling in the walls of the hole. High levels of regional stress are not needed to cause spalling.

Regarding the stress directions, it has been shown from observations of oil well breakouts that the direction of the maximum horizontal compressive stress is NE-SW (Bell and Gough, 1979, 1981; Gough and Bell, 1981, 1982) throughout the sedimentary basin of Alberta, including the Oldman River Dam Project area. This is consistent with the forces which resulted in thrust faulting during the Laramide orogeny.

6.3 Engineering Considerations

In our understanding, the term 'jiggling' is not a commonly used and defined technical term, either in engineering or geology, and hence, its precise meaning is not clear. From Dr. Greggs' use of the term, it appears to refer to movements that originate in the basement, and occur sporadically along faults over geologic time. In dam engineering studies the frequency and location of fault movement is extremely important as discussed below.

Engineering geologists and geotechnical engineers responsible for field investigations and dam design understand that faults, if they exist, are important because they may have a potential for renewed movement which may cause damage to structures. Accordingly, regional geology studies are normally made to investigate the existence of faults.

Normal Practice

If faults are found at the ground surface in a proposed dam project area, there are two alternatives - to relocate the project structures away from the area of the faults - or, if this is not feasible, to

a) investigate the potential for renewal movement along the exposed faults and,

b) if movement is considered possible, evaluate the impact of the potential movement on the project structures.

Standard engineering procedure in the second alternative is to first determine the probability of renewed movement. This is done by assessing the age of the most recent fault movement. If this can be proven to have occurred in the relatively distant geological past, i.e., there has been a very long period of no-fault movement, it can safely be assumed that renewed fault movement will not occur in the foreseeable future. Hence, the probability of future renewed movement is negligible, and the project can safely be constructed. The age of the most recent faulting is generally determined by establishing the age of the oldest unfaulted stratum. If faults are at or near the surface, this may require age-dating of the oldest unfaulted unconsolidated sediments or even overburden.

Engineering standards have set certain minimum time periods of no-fault movement for certain types of project structures. The time period assigned varies according to the potential hazards associated with the project structure. The time periods for dams and nuclear plants are given below (Idriss 1985).

Structure	**Organization**	**Time Period**
Dams	U.S. Bureau of Reclamation	- 100,000 yr
	U.S. Corps of Engineers	- 35,000 yr
Nuclear Plants	U.S. Nuclear Regulatory Commission	- 500,000 yr for multiple displacement - 35,000 yr for single displacement

In the case of deeply buried faults, it is normally assumed in dam engineering studies that these faults will not propagate to the ground surface in the foreseeable future, i.e., the fact that they have not already propagated to the ground surface indicates that they will not propagate upwards to the ground surface in the foreseeable future. It is, however, accepted in dam engineering studies that deeply buried faults may exist and be subject to renewed movement. This would usually cause earthquakes; the resulting vibrations would cause ground motion to occur beneath the project structures. Accordingly, a seismicity study is normally done to determine the maximum ground acceleration to be expected at the site ground surface. The project structures are then designed to accommodate this acceleration.

Recent studies (Stein and Yates, 1989) suggest a greater frequency of earthquake occurrence over deep anticlinally folded sedimentary rock sequences. These studies suggest that deeply buried faults in the anticlines, and the anticlines themselves, are slowly propagating upwards towards the ground surface. These findings may affect future seismicity studies for some projects in areas of folded sedimentary rock.

Application to Oldman River Dam Project

Dr. Greggs describes vertical fault activity originating in the basement and implies that the faults propagate upwards from the basement into the overlying sedimentary rock.

We have concluded in Section 5 that there are no inclined or vertical faults of any engineering significance at the ground surface in the lower reservoir and dam site area. This implies that no near-surface faults exist and hence, no near-surface fault movements need be considered.

It is possible, however, that deep buried faults may exist; according to the regional studies by independent investigators, such faults, would be below the Porcupine Hills Formation which is 54-66 million yr old. This indicates that there has been no fault movement in the lower reservoir and dam site areas for at least 54 million years. This far exceeds the no-fault movement time criteria specified by either the U.S. Bureau of Reclamation or U.S. Corps of Engineering.

Again, if such buried faults should exist, the seismicity study determined that the maximum ground acceleration resulting from movement along hypothetical faults beneath the dam site would be significantly less than that resulting from the maximum credible earthquake. This aspect is further discussed in Section 6.5.

Regarding the recent studies by Stein and Yates (1989) and the possibility of upward propagation of the buried faults, this does not apply to the Oldman River Dam Project because there are no known anticlinal structures beneath the project area.

We conclude that from the engineering point of view, the Oldman River Dam Project structures are adequately designed against potential movements along deeply buried faults, if they exist.

6.4 Stress-Induced Fault Movement

Dr. Greggs implies that the existing regional stresses in the rock will cause movement on his alleged vertical faults.

We consider that, even if Dr. Greggs' NW-SE and NE-SW-oriented vertical faults and NE-SW horizontal compressive forces were to exist, movement along the faults would be theoretically impossible. The reason is that the shear stresses required to cause relative displacement would be zero on the postulated fault planes. Shear stresses on planes parallel and normal to the principal stress directions are zero by definition.

Although Dr. Greggs appears to believe that the stress levels are high enough to initiate movement on existing faults, Gough (1989), describes a relaxed state of stress where the stresses are low and not significantly different from one principal stress direction to another. In this light, Gough states "the probability of movement on any faults, under these stresses, is small." He further states "such a stress field indicates very low levels of tectonic activity and of seismic risk. This is in general agreement with the very low seismicity in Alberta."

6.5 Earthquake-Related Fault Movement

Dr. Greggs suggests that earthquake-related fault movement may cause ground surface instability and damage to the project structures.

In our view, earthquakes are seismic events that occur at various depths in the earth's crust and in which relatively large amounts of stored strain energy are released. The energy release usually occurs during sudden shear movement along one or more fault planes. Either new or pre-existing fault planes may be involved in an earthquake. In some areas, the distribution of earthquakes suggests they may be associated with a prominent fault that is expressed at ground surface. Conversely, earthquakes occur in places where there are no known significant tectonic faults, either at the surface or below.

A seismicity study was done by Wolofsky and Gough in 1985 and updated in 1989 to assess the magnitude of the ground acceleration to be expected at the Oldman River dam site as a result of potential earthquake activity in the future. The dam site is located in a quiescent seismo-tectonic zone where few major faults are known to exist. Immediately to the west is the Southeastern British Columbia seismo-tectonic zone (SBC), wherein several earthquakes generally not greater than Magnitude 4 have occurred. This zone includes the folded and faulted Disturbed Belt.

According to the Geological Survey of Canada, no earthquakes have occurred within 35 km of the Oldman River dam site since 1899; this zone includes the entire project area. One earthquake of Magnitude 3 and four earthquakes between Magnitudes 3 and 4 have occurred between 35 km and 50 km from the dam site. Beyond 50 km several earthquakes have occurred between Magnitudes 3 and 4, one between Magnitude 4 and 5 and one between Magnitude 5 and 6, the largest, 135 km south of the project. Most of these are in the Disturbed Belt in Canada and its continuation into the United States.

These studies indicate that the Oldman River Dam Project is located in a relatively quiescent seismo-tectonic zone wherein the relatively few earthquakes that do occur, are apparently randomly located, i.e., they are not related to known faults. Since no earthquake-related fault movements have been observed at the ground surface anywhere in the seismo-tectonic zone, the movements must occur along buried faults. The level of seismic activity in the project area is very low, according to Gough (1989). Hence, the probability of earthquake-related movement along buried faults is similarly very low. The probability of the same fault movement propagating upwards to the ground surface in the lower reservoir and dam site area is virtually nil.

Vibrations resulting from earthquake-related fault movements occurring below the ground surface are taken into account in the seismic design of the dam and other related structures. Project structures are designed to withstand a selected magnitude of ground acceleration determined from probabilistic and deterministic methods. These methods are standard procedures in dam engineering.

It should also be noted that in 1985 a microseismic network was established in and around the Oldman River Dam Project area. Results of seismographic monitoring to date confirm the conclusion that the project is located in a quiescent area.

6.6 Reservoir-Induced Fault Movement

Dr. Greggs suggests that movement may occur along vertical fault planes as a result of reservoir impounding at the Oldman River Dam.

Reservoir water impounding at dam projects has induced seismic activity in a small number of cases. Gough (1978) has discussed worldwide reservoir-induced seismicity (RIS) phenomena, and Wolofsky and Gough (1989) have studied the potential effects of RIS at the Oldman River Dam Project.

Wolofsky and Gough (1989) point out that:

1) movements may occur along existing faults, under or near the reservoir due to the weight of the reservoir water, and

2) movements may occur along existing faults at depth caused by pore water pressure increase that results in a reduction of effective normal stress and a corresponding decrease in shear strength, along the faults.

Gough (1978) has shown that reservoir impounding theoretically causes increased stability, i.e., less tendency to move, along thrust faults beneath a reservoir. In contrast, he shows decreased stability along normal faults. This assumes that when the reservoir is filled the stress directions and magnitudes are the same as those that existed when the faults were first formed. Near-failure stress conditions are also assumed.

RIS refers to earthquakes triggered by a newly-impounded reservoir or by changes in the reservoir level. The probability of reservoir-induced fault movement relates to the probability of natural earthquake-related fault movement and depends upon the fault types. Therefore, the probability of a thrust fault being activated by the reservoir is very slightly less than the probability of occurrence of natural earthquake-related fault movement. Similarly, the probability of activating a normal fault is very slightly greater than the probability of occurrence of natural earthquake-related fault movement. Hence, the probability of reservoir-induced fault movement is essentially the same as for natural earthquake-related fault movement, as discussed in Section 6.5.

Should reservoir-induced fault movement occur at depth, the resulting ground acceleration at the dam site is not expected to exceed the ground acceleration determined from deterministic and probabilistic methods and for which the dam and related structures have been designed.

Wolofsky and Gough (1989) compare RIS at the Oldman River Dam Project reservoir with dam reservoirs where RIS has occurred. The majority of dam projects where RIS has occurred have reservoirs deeper than that at the Oldman River Dam Project. However, RIS has also occurred in several reservoirs smaller than the Oldman River dam reservoir.

Wolofsky and Gough (1985, 1989) have examined data on existing reservoirs within 280 km (mostly less than 200 km) of the Oldman River dam site, where it may be assumed that tectonic stresses are similar to those in the project area. Several of these are located in the Disturbed Belt, where the level of seismicity is markedly higher than at the Oldman River Dam Project area. Reservoir size ranged from large to small. None of the projects have registered any RIS activity. It is to be noted that no RIS activity occurred at the Mica Creek and W.A.C Bennett dams located in the more seismically active terrain in the Rocky Mountains of British Columbia. Both reservoirs are much larger and deeper than at the Oldman River Dam Project.

In conclusion, there is no reason to expect that the Oldman River dam reservoir will induce fault movement, and every reason to expect that it will not. If such movement were to occur, it would not cause an offset at the ground surface. Nor would the associated earthquake ground motions be appreciable, compared with the much more severe maximum credible earthquake ground motions that the structures have been designed to withstand.

6.7 Other Movements

Referring again to Dr. Greggs' alleged 'jiggling' movements, a further note is in order. Dr. Greggs infers that movement on basement fractures will cause corresponding movements at the ground surface and damage the structures thereon.

Dr. Greggs' report appears to imply that many existing structures constructed in Alberta could be subject to damage. This would include tall buildings and chimneys, earth and concrete dams, tunnels and power plants, all of which are very sensitive to ground movement and are founded on sedimentary rocks that overlie the same basement rocks that underlie the Oldman River Dam Project. The record shows that these structures are performing well and there are no reports of any apparent signs of distress, as might be expected from reading Dr. Greggs' report.

6.8 Foundation Grouting

Dr. Greggs states that "Any tectonic stresses, regional or local, will act on the existing fractures, creating further fracture permeability and porosity. In areas where a more brittle 'rock' has been introduced into the bedrock (by injection of grout), the more brittle component will fracture preferentially. Any fracture permeability will cause leakage."

According to the results of the geological and geotechnical investigations performed at the Oldman River dam site, the foundation conditions are not unusual in terms of permeability, considering the effects of stress relief and valley rebound. No faulting of any significance has been found, as discussed earlier.

Foundation grouting is the accepted engineering procedure performed in dam foundations in jointed rock to seal the joints and reduce the potential underseepage to acceptable levels. A foundation grouting program has been designed for the Oldman River Dam Project, taking into account the geological and geotechnical conditions, as well as the hydraulic head of the reservoir.

Presently, the foundation grouting at the dam site is approximately one half completed. Check procedures to date indicate that the required reduction in foundation permeability is being achieved.

7.0 SLAKING

Dr. Greggs has raised the question of "what the effect of wet 'slaking mudstones' present both over and under the fractured sandstone unit will be on the stability of the bounding valley walls."

In our understanding, the term 'slaking' refers to the deterioration of mudstone from weathering and erosion in air and water. Most slaking results from alternating wetting and drying.

It has always been recognised that the claystones and siltstones of the Porcupine Hills and Willow Creek formations in the project area are rock types that slake and that the processes of slope evolution include slaking of relatively weaker mudrocks and undercutting of jointed sandstone beds. Further, the effects of reservoir impoundment, fluctuating reservoir water levels and wave erosion on the stability of valley slopes are also well understood.

Accordingly, the natural and excavated slopes have been designed according to accepted engineering practice. The design analyses have considered stability of the rock mass against sliding, slope deterioration through erosion, slaking and block failure, the consequences of such deterioration and the need for slope protection.

Most reservoir slopes will be left in their existing natural condition. Potential erosion and slope flattening in the future has been allowed for in design. In excavated slope locations, such as above the tunnel portals, at bridge piers and other critical areas, where prevention of erosion is essential, the mudrocks will be protected by filters, rock fill and riprap.

8.0 CONCLUSIONS

- Thre is no evidence of inclined or vertical faulting of any engineering significance at ground surface in the lower reservoir and dam site areas . Rocks in these areas are characterized by stratigraphic continuity and the absence of stratigraphic offsets. Mapping by government geologists, extensive project studies performed since 1985 and findings of a group of expert geologists, geophysicists and engineers support this conclusion.

- Evidence of deformation taken from borehole core description, which allegedly indicates vertical faulting, has been misinterpreted or misunderstood. The deformation features cited by Dr. Greggs are caused by horizontal shearing along the near-horizontal bedding planes. Bedding plane shearing is inconsistent with Dr. Greggs' postulated vertical faulting.

- The only near-vertical fractures found in the project area are joints, which show no shear displacement and hence are not faults.

- No credible reason has been found to suspect that the lineaments recognized by Dr. Greggs in the lower reservoir and dam site areas bear any relation to near-surface faults.

- The stresses in the rock beneath the project area are not high enough to initiate movement on buried faults, should they exist.

- The probability of future earthquake-related or reservoir-induced movement on buried faults, should they exist, in the project area is very low. The probability of the same fault movement propagating upwards to the ground surface in the lower reservoir and dam site areas is virtually nil. The latter conclusion is supported by the fact that no faulting has occurred in the lower reservoir and dam site areas for at least 54 million years, as attested by the absence of inclined or vertical faulting in the Porcupine Hills Formation.

- The potential effects of slaking mudstones around the reservoir rim has been taken into account in design.

- A grouting program has been designed to seal the joints in the dam foundation and abutments which will reduce the potential underseepage to acceptable amounts.

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APPENDIX A

Contributions by UMA/Acres and Alberta Public Works, Supply and Services geologists, geophysicists and engineers

APPENDIX A1	Dr. D.K. Bingham, P.Geoph.
APPENDIX A2	Mr. D.M. Davison, P.Eng.
APPENDIX A3	Dr. D.I. Gough
APPENDIX A4	Dr. J.D. Mollard, P.Eng., P.Geol.
APPENDIX A5	Dr. Ozoray, P.Geol.
APPENDIX A6	Dr. K.W. Savigny, P.Eng., P.Geol.
APPENDIX A7	Dr. L. Wolofsky

APPENDIX A1

Dr. D.K. Bingham, P.Geoph.

Dr. D.K. Bingham installed and has responsibility for operating the micro-seismic instrumentation network in the Oldman River Dam Project area which is integrated with the Turtle Mountain (Frank Slide) monitoring system. Dr. Bingham obtained his B.A. in mathematics and physics from Yale University in 1962 and his M.S. and Ph.D. degrees in geophysics from the University of Alaska in 1967 and 1971, respectively. He is currently Head of the Technical Support Section, Hydrogeology Branch of Alberta Environment. He has been involved in various geophysical research projects in glaciology, paleomagnetism, geomagnetism and volcanology. With Alberta Environment he has been involved in investigations of induced seismicity related to petroleum industry developments.

Alberta MEMORANDUM

ENVIRONMENT

TECHNICAL SERVICES DIVISION

FROM D.K. Bingham, P. Geoph.
Head, Technical Support Section
Hydrogeology Branch

OUR FILE REFERENCE 50-2-2-7-9

YOUR FILE REFERENCE

TO J.W. Thiessen, P. Eng.
Oldman River Dam Project
Reservoir Development

DATE May 8, 1989

TELEPHONE

SUBJECT Review of "Preliminary evaluation of the bedrock structure - Oldman River Dam site area Southern Alberta" prepared by R.G. Greggs for The Friends of Oldman River

This memo updates my earlier memo of 11 April 1989 and is identical to it except where it has been revised following the site visit of 17-18 April.

The "Geological Background" section of this report summarizes, using copious references, the well known fact that the Western Canadian Basin is under a dominant NE-SW regional stress field which in turn is supposedly related to a prevalent NE-SW/NW-SE system of joints or faults. Whether these are joints or faults is left open and in what follows in the report there is much confusion between these terms.

In the "Tectonic Deformation" section, a few out-of-context excerpts from the drill core records of the Preliminary Engineering Report are used to show rather unconvincingly that the project area is riddled with signs of tectonic deformation. Of course the area is under stress and there has been deformation, but the pervasiveness of the fracturing and faulting which is implied is probably exaggerated.

The locations of the five major faults in the project area described in the next section were not verified by the field studies conducted during the April 18-19 site visit. Careful examination of several field localities which should have shown evidence of Greggs' faults A, B, C, X, or Y failed to turn up the slightest indication of faulting. Jointing was seen at all locations and is, in fact, prevalent at all rock exposures in the reservoir area; this is entirely normal in these rock types and geological environment. It is indeed probable that Dr. Greggs is somewhat confused about the difference between faults and joints.

From: Douglas Bingham, P. Geoph.

To: J.W. Thiessen, P. Eng.

Re: Review - Oldman River Dam

The faults have been drawn on Greggs' map following the slimmest of evidence. It is preposterous to identify Fault A with the Bridger Fault mapped by Maughan and Perry (1986) as a lineament stretching across Colorado and Wyoming when the nearest mapped part of this fault is nearly 500 km away. In any case, I question the work of Maughan and Perry (although I have not seen their complete paper) because their Figure 2 reproduced in Greggs' report, showing many lineaments over 1000 km long neatly ruled at regular intervals across the map, shows no relationship whatever to the lineament map of the same area by Downey et al (1987) also reproduced by Greggs. The latter map showing much shorter, more irregularly spaced lineaments, would appear for this reason alone to have greater validity.

Only one tiny, steeply dipping, normal fault was found by the consulting geologists for the project in the dam site area; this had unfortunately already been removed by excavation for the spillway at the time of the site visit but we visited its location, viewed photographs of it, and discussed its significance at length. The very fact that a few metres of rock excavation had removed all evidence of the fault indicates how minor a fault it was. It was clearly a very local fault related to valley rebound and/or stress relief related to down cutting of the river valley. Again, this is an entirely normal occurance in this geological environment.

The penultimate section "Implications for site stability" raises the spectre of fault movements and earthquakes. To my knowledge there is no evidence of major movements occuring on any surface or near surface fault in the southern Alberta Basin since at least glacial times. Therefore the likelihood of movement, either seismically or aseismically (by creep), on any of these faults would appear to be remote.

In any case, should such movement occur, it could not be described as "jiggling" as Greggs has indicated. Jiggling implies an oscillatory or back and forth movement which is contrary to accepted theory of earthquake motion. Because rock is an elastic material, the sudden single sharp movement at the source of an earthquake produces an outward radiating elastic disturbance which quickly becomes oscillatory in nature, but the relative movement across the fault is not oscillatory.

page 2...

From: Douglas Bingham, P. Geoph.

To: J.W. Thiessen, P. Eng.

Re: Review - Oldman River Dam

The ambient seismicity level in southwestern Alberta is low (cf. attached map prepared by E.R. Kanasewich at the University of Alberta). Since the fall of 1986, Alberta Environment has operated a 3 station telemetred event triggered seismic array bracketing the future Oldman River reservoir. This array is integrated with the 6 station Turtle Mountain array 35 km to the west and is recorded at the Frank Slide Interpretive Centre (cf. map attached). It has detected many of the dam construction blasts, but to date has only detected a single, small apparently local earthquake which occured on 6 December, 1988 and some very local microseisms related to Turtle Mountain. This event may ultimately be found to have been a blast, but it is not near the dam construction site. It is currently under investigation. In any case, the local microseismicity level is still considered to be very low.

As to the possibility of reservoir induced seismicity raised by Greggs in referring to fault "greasing" by increased pore pressure at depth, this can only occur if there is sufficient ambient stress available to release to cause an earthquake. The low level of historical seismicity indicates that such tremors, were they to be induced, would be very small. Of the 33 documented cases of reservoir induced changes in seismicity listed by Simpson (1976)(cf table attached) only four involve a head of water (which translates directly into increased pore pressure at depth) smaller than the 67 m maximum projected head of the Oldman River Dam. About half of these documented cases involve reservoir volumes smaller than that of the future Oldman River reservoir (493 x 10 m).

The potential for damage to the dam due to regional seismicity was adequately addressed by the Seismicity Study produced by UMA/Acres in 1985. I believe this study used the correct methodology to arrive at the maximum credible ground motion at the project site and that, therefore, the dam has been designed to withstand same.

After two very intensive days spent in examining the site and drill cores and in discussing the local and regional geophysics and geology with both the geologists and engineers intimately involved in this project and with the other geologists, geophysicists and engineers called in for the purpose of reviewing the concerns raised by Greggs' report, I conclude that:

page 3...

From: Douglas Bingham, P. Geoph.

To: J.W. Thiessen, P. Eng.

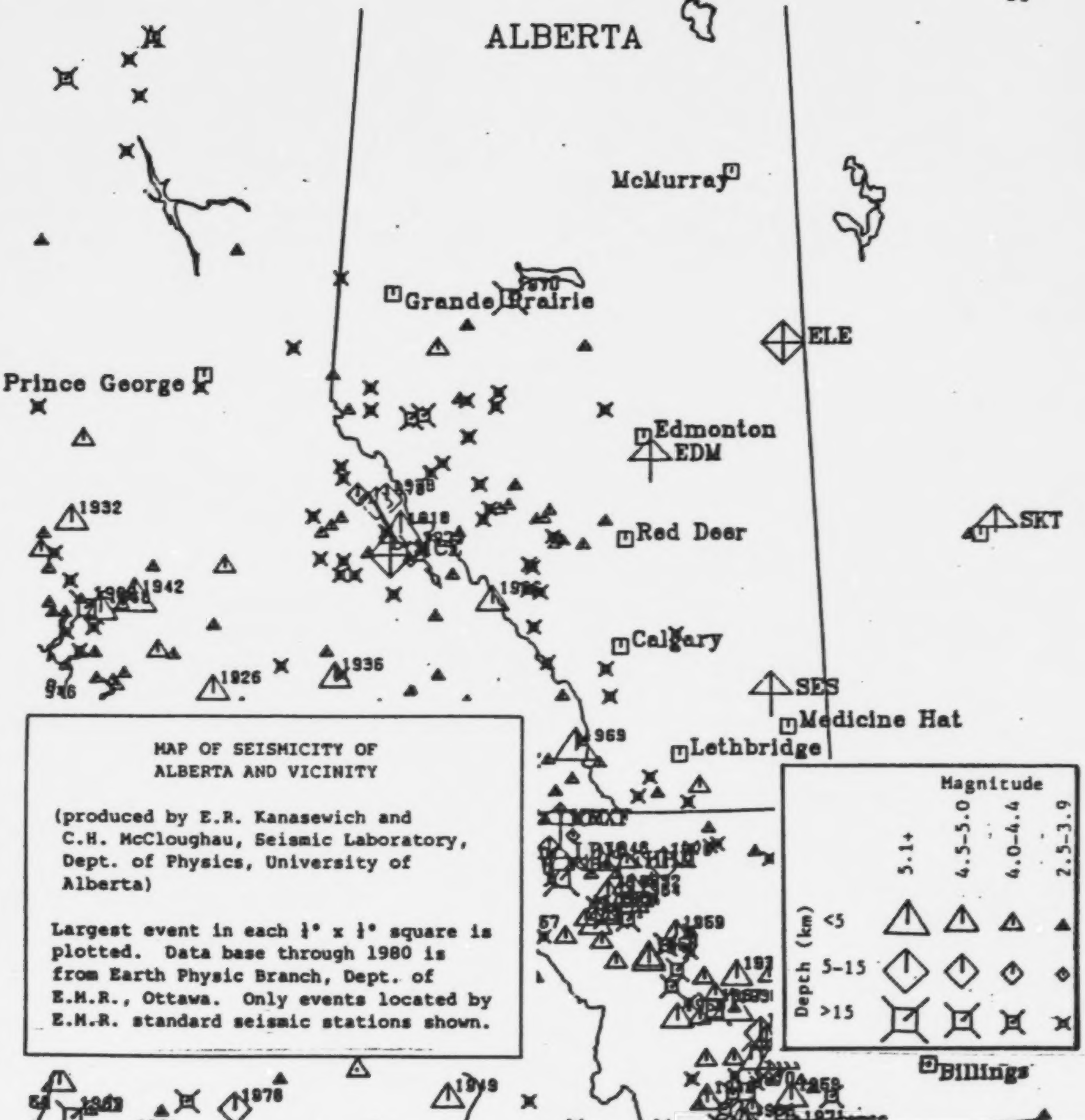
Re: Review - Oldman River Dam

a) The report by Dr. R.G. Greggs, at best, is not very carefully written or well thought out and, at worst, is blatently incorrect or misleading in many aspects. The quality of the report is poor enough to lead one to question Greggs' competence as a professional geologist.

b) I have complete confidence that the engineers and geologists who have worked with this project since its inception have done a careful and fully adequate job with understanding the local and regional geology sufficiently well to design and build a safe dam.

Douglas K. Bingham, P. Geoph.

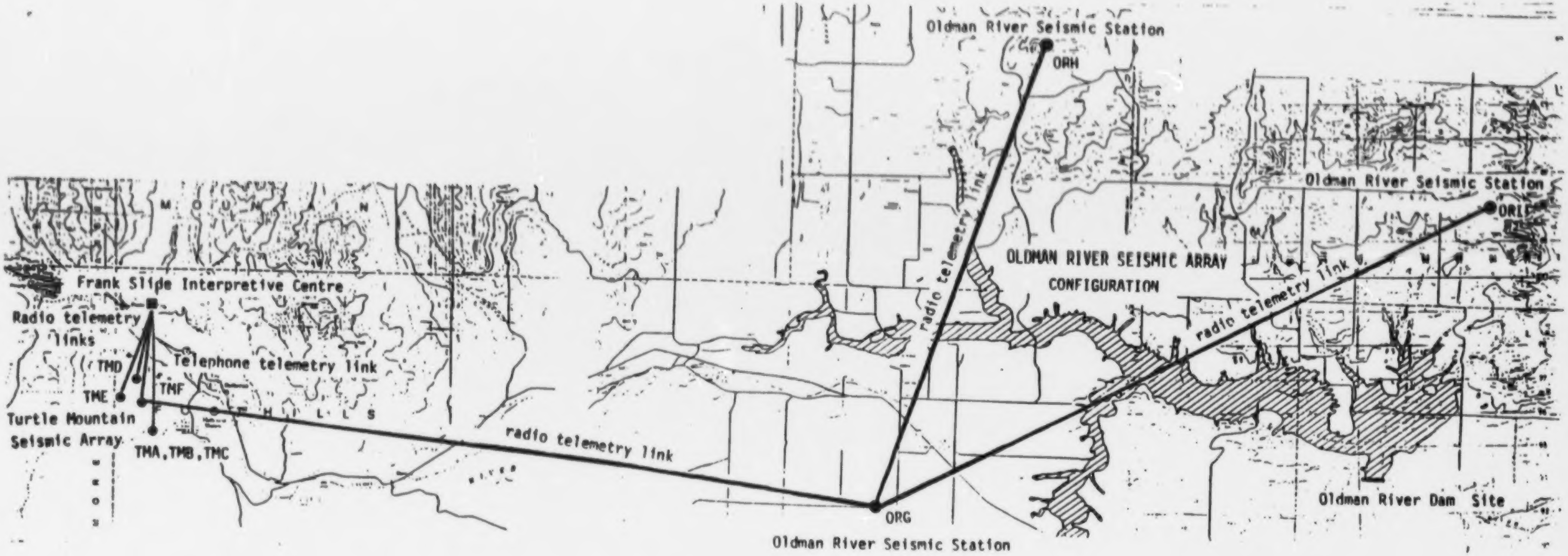
DKB/vlc


ALBERTA
McMurray
Grande Prairie
1970
ELE
Prince George
Edmonton
EDM
1932
Red Deer
SKT
1942
1926
1936
Calgary
SES
Medicine Hat
1969
Lethbridge
1959
Magnitude
5.1+
4.5–5.0
4.0–4.4
2.5–3.9
Depth (km)
<5
5-15
>15
Billings
1976
1961
1949
1963
1944
OREGON
1959
Challis area
Boise
IDAHO
WYOMING
1965
1961
1958
1928

MAP OF SEISMICITY OF
ALBERTA AND VICINITY

(produced by E.R. Kanasewich and
C.H. McCloughau, Seismic Laboratory,
Dept. of Physics, University of
Alberta)

Largest event in each ½° x ½° square is plotted. Data base through 1980 is from Earth Physic Branch, Dept. of E.M.R., Ottawa. Only events located by E.M.R. standard seismic stations shown.


OLDMAN RIVER SEISMIC ARRAY
CONFIGURATION
Oldman River Seismic Station
ORH
Oldman River Seismic Station
ORI
radio telemetry link
radio telemetry link
radio telemetry link
M O U N T A I N
F O O T H I L L S
Frank Slide Interpretive Centre
Radio telemetry links
Telephone telemetry link
TMD
TME
TMF
Turtle Mountain Seismic Array
TMA,TMB,TMC
ORG
Oldman River Seismic Station
Oldman River Dam Site

Dam name	Location	Height of dam (m)	Volume of reservoir $(\cdot 10^6\ m^3)$	Year of impounding	Year of largest earthquake	Magnitude or intensity	Reference
Major induced earthquakes							
Koyna	India	103	2708	1964	1967	6.5	1,2,3
Kremasta	Greece	165	4750	1965	1966	6.3	1,2,3,4
Hsinfengkiang	China	105	10500	1959	1962	6.1	1,5
Oroville*	U.S.A. (Calif.)	236	4295	1968	1975	5.9	6
Kariba	Rhodesia	128	160368	1959	1963	5.8	1,2,3,7
Hoover	U.S.A. (Ariz.)	221	36703	1936	1939	5.0	1,2,3,8
Marathon	Greece	63	41	1930	1938	5.0	1,2,3,4
Minor induced earthquakes:							
Benmore	New Zealand	118	2100	1965	1966	5.0	1,9
Monteynard	France	155	240	1962	1963	4.9	1,2,3
Kurobe	Japan	186	199	1960	1961	4.9	1,10
Bajina-Basta	Yugoslavia	89	340	1966	1967	4.5-5.0	1,3
Nurek	U.S.S.R.	317	10400	1969	1972	4.5	11
Clark Hill	U.S.A. (S.C.)	67	2500	1952	1974	4.3	12
Talbingo	Australia	162	921	1971	1972	3.5	1,14
Keban	Turkey	207	31000	1973	1974	3.5	15
Jocassee	U.S.A. (S.C.)	133	1430	1972	1975	3.2	13
Vajont	Italy	261	61	1961	1963		1,2,3
Grandval	France	88	292	1959	1963	V	1,2,3
Canalles	Spain	150	678	1960	1962	V	1,2,3
Changes in micro-earthquake activity:							
Kamafusa	Japan	46	45	1970		<2.5	16
Pieve de Cadore	Italy	112	68	1949		2.0	1,2,3
Grancarevo	Yugoslavia	123	1280	1967		1.0-2.0	1,3
Hendrik-Verwoerd	S. Africa	88	5954	1970		<2.0	1,17
Schlegeis	Austria	130	129	1971		<0.0	18
Transient changes in seismicity:							
Oued Fodda	Algeria	101	228	1932			1,2,3
Camarilles	Spain	44	40	1960	1961	3.5	1,2,3
Piasta	Italy	93	13	1965	1966	VI-VII	1,2,3
Vouglans	France	130	605	1968	1971	4.5	1,2,3
Contra	Switzerland	220	86	1965	1965		1,2,3
Decreased activity:							
Tarbela	Pakistan	143	13687	1974			19
Flaming Gorge	U.S.A. (Utah)	153	4647	1964			20
Glan Canyon	U.S.A. (Ariz.)	216	33305	1964			20
Anderson	U.S.A. (Calif.)	72	110	1950			21

Other possible cases:

Height in meters follows dam name (n.a. = not available).

U.S.A.—Shasta (183), Calif.; San Luis (116), Calif.; Palisades (82), Utah; Clark Canyon (40), Mont.; Kerr (n.a.), Mont.; Cabin Creek (n.a.), Colo.; Rocky Reach (n.a.), Wash.

Australia—Eucumbene (116); Warragamba (137).

Pakistan—Mangla (116)

Spain—El Grado (130)

India—Kinnersani, Parambikulam, Sharavathi, Ukai, Ghirni, Mula (all n.a.)

References: 1 = Gupta and Rastogi (1976); 2 = Rothé (1970, 1973); 3 = Božović (1974); 4 = Drakopoulos (1974); 5 = Chung-kang et al., (1974); 6 = Bufe et al., (1976); Morrison et al., (1976); 7 = Gough and Gough (1970b); 8 = Carder (1945); 9 = Adams 10 = Hagiwara and Ohtake (1972); 11 = Soboleva and Mamadaliev (1975); 12 = Talwani (1975); 13 = P. Talwani (pers. comm., 1976); 14 = Timmel and Simpson (1972); 15 = N. Tilford (pers. comm., 1975); 16 = Suzuki (1975); 17 = Green (1973); 18 and Fuchs (1974); 19 = Jacob et al., (1976); 20 = Mickey (1973); 21 = Bufe (1975).

*The relationship between the Oroville earthquake and the filling of the reservoir is not as clear as for the other major induced earthquakes. See further comment.

from: Simpson, D.W., 1976. Seismicity changes associated with reservoir loading. In: W.G. Milne (Editor),-Induced Seismicity. Eng. Geol, 10(2—4): 123—160.

APPENDIX A2

Mr. D.M. Davison, P.Eng.

Mr. Davison is Vice President and Manager, Alberta Region of Klohn Leonoff Ltd. and is the senior engineer responsible for geotechnical designs of the reservoir related works of the Oldman River Dam Project. He obtained his B.A.Sc. in civil engineering from the University of British Columbia in 1958 and his SM from Massachusetts Institute of Technology in 1959. He has been involved with a number of dam projects including the recently completed Forty Mile Coulee dams in southern Alberta. He has worked on feasibility studies for the Dickson Dam in Alberta, design and construction of the Strutt Lake hydroelectric dams in the Northwest Territories, construction of Squaw Rapids hydroelectric dam in Saskatchewan, investigations for several dams on the Nelson River in Manitoba and investigation and construction of several dams in British Columbia.

Stanley

Stanley Associates Engineering Ltd.
2633 - 37 Avenue N.E.
Calgary, Alberta T1Y 5V7
Phone (403) 291-2100 Telex 03-821172

May 31, 1989
File No.: 71-796-01

UMA Engineering Ltd.
17007 - 107 Avenue
Edmonton, Alberta
T5S 1L8

Attention: Mr. D.B. Chalcroft, P.Eng.

Gentlemen:

Reference: Oldman River Dam/Reservoir Related Works
Greggs and Associates Report on Oldman
River Dam Site Area
Klohn Leonoff Comments Regards
Reservoir Study Data

As a matter of context, Stanley Associates Engineering Ltd. was the Prime Consultant on the Reservoir Related Works associated with the Oldman River Dam. This included Reservoir Integrity and Slope Stability Studies of the Reservoir from 1 km upstream of the dam centreline to the Reservoir limits.

This work was undertaken on Stanley Associates' behalf by Klohn Leonoff Ltd. During their study, a related Regional Geology Report was prepared on their behalf by Mollard & Associates.

Both a Klohn Leonoff Ltd. representative and a Mollard & Associates representative participated in the recent meeting to review comments made by Greggs & Associates related to their reports. In this regard, enclosed is a letter from Klohn Leonoff Ltd. concerning comments made by Greggs & Associates on matters referred to in Klohn's Reservoir Study.

We trust this supplementary information will be helpful to you.

Yours truly,

STANLEY ASSOCIATES ENGINEERING LTD.

K.A. Hamman, P.Eng.
Project Coordinator

KAH:pn

cc: J.W. Thiessen, Project Manager

KLOHN LEONOFF
CONSULTING ENGINEERS

OUR FILE: PA 2445.100 May 4, 1989

UMA Engineering Ltd.
17007 - 107 Avenue
Edmonton, Alberta

Mr. D.B. Chalcroft, P.Eng.

Oldman River Dam Reservoir Related Works
Greggs and Associates Report on Oldman River Dam Site Area

Dear Sir:

This letter will briefly comment on the points raised by Greggs & Associates regarding the data gathered for the reservoir study and the stability of the reservoir slopes.

1.0 Test Hole Logs

Some of the test holes around the reservoir identify slickensides, brecciation, clay gouge and one classification used the term fault in connection with the above terms. These zones of disturbance can be found in all the test holes drilled around the reservoir. There are possibly more references to the weak zones in the Willow Creek formation which has the largest percentage of claystone in its stratigraphic profile. These zones of weakness are interpreted as weak shear planes which have been encountered on many projects in Alberta and British Columbia and have been observed in large diameter drill holes (1 m diameter), open excavations and tunnels. The disturbed shears are believed associated with disturbance of the near surface rock during glacial unloading, valley rebound, and other tectonic effects. The condition is not unique to the Oldman River area.

2.0 Reservoir Integrity

The potential for deterioration of the valley slopes due to erosion and instability has been identified in our Reservoir Boundary Study dated December 1986. Subsequently the design of all structures located within the reservoir have considered both the potential for instability and erosion.

In particular the design of the bridges and pipelines crossing the reservoir have addressed the potential for weak shear planes in the bedrock by construction of stabilizing granular fills against the valley slopes. The stabilizing fills will also serve to protect the abutments against erosion.

In areas of no development around the reservoir, protection against either erosion or potential slope instability is not considered economically feasible. Instead the philosophy has been to establish a perimeter buffer zone in which development is limited. A recommended reservoir boundary line was presented in our 1986 report and as a minimum all land within this boundary has been purchased and is under Government control.

Yours very truly,

KLOHN LEONOFF LTD.

DONALD M. DAVISON, P.Eng.
Vice President, Alberta Region

DMD/sh

APPENDIX A3

Dr. D.I. Gough

Dr. D. I. Gough collaborated with Dr. L. Wolofsky to provide the seismicity input to the design of the Oldman River Dam Project. His main responsibility was to study the potential for reservoir induced-seismicity caused by the project. Dr. Gough obtained his B.Sc. and M.Sc. in physics from Rhodes University College in 1943 and 1947, respectively. He obtained his Ph.D. in geophysics from the University of the Witwatersrand in 1953. He is currently Professor Emeritus of the Department of Physics at the University of Alberta. He was president of the International Association of Geomagnetism and Aeronomy, 1983-87. In 1983 he was recipient of the J. Tuzo Wilson Medal of the Canadian Geophysical Union. He was awarded the Chapman Medal of the Royal Astronomical Society, London in 1988 and the Krahmann Medal of the South African Geophysical Association in 1989. He has authored or co-authored some 94 papers, including several major contributions on reservoir-induced earthquakes.

4 May 1989

11747 - 83rd Avenue
Edmonton, Alberta
T6G 0V2

UMA Engineering Ltd.
17007 107 Avenue
Edmonton, Alberta
T5S 1G3
ATTENTION: Mr. D.B. Chalcroft
Mr. B.L. Baggott

Dear Sirs,

I have read the report by Greggs and Associates to the Friends of the Oldman River, dated February, 1989. I offer the following comments:

1. The Greggs Report does not always make a clear distinction between the terms fault and joint. Thus the known, well understood, superficial fractures called joints, which have dominant directions NW-SE and NE-SW and subsidiary directions N-S and E-W in Alberta east of the Rocky Mountains, appear to be regarded as evidence of deep vertical faults in that Report. The distinction is important. Joints are extensional fractures arising near the surface of the Earth during uplift and folding. Faults are major fractures on which shear displacement has occurred. The failure to distinguish between these two very different types of fracture, in the Greggs Report, does not serve the cause of accurate description of the tectonic situation.

2. In my opinion the discussion on pages 16-18 of the Greggs Report presents at most suggestive evidence that the five faults postulated, in the project area, actually exist. Lineations may or may not indicate faults. Geomorphological features such as scarps and river beds may or may not be controlled by faults. Seismic refraction results do not usually resolve faults, which require high density and high quality seismic reflection to trace them. Seismic data for the area considered in the Greggs Report are from refraction profiles only (top of page 6), so that seismic indications of faults can only be suggestive at best, and are open to alternative interpretations.

3. If these faults do exist, the next question is whether they are active, that is to say, whether movement is occurring across them. They will be active if the stresses existing in the crust are large enough and suitably oriented. While the level of seismic activity in the project area is very low, as shown in the Seismicity Study of 1985, the remote possibility of an increase of such activity was one reason for the

recommendation of seismic monitoring of the area, in that Study. Such seismic monitoring is being carried on by Alberta Environment. Dr Bingham reports (April, 1989) that the seismic records from the monitoring network indicate that the project area is seismically extremely quiet. Up to April, 1989, only one seismic event had been detected which was neither a distant earthquake nor an identified blast. That event was so small that its nature is uncertain. If it is a small earthquake, its magnitude, judged from the duration of the signal and other characteristics, is 1.5 or less, according to Dr Bingham. It may have been a blast but if so, it was in an unusual location south of the project area.

4. The regional stress system is considered on pages 8 and 9 of the Greggs Report. On page 8 the Report quotes an explanation, by Babcock (Bulletin of the American Society of Petroleum Geologists, 62, 1111-1126, 1978), of the wellbore breakouts as caused by penetration by the well of an existing fracture at depth. This explanation was incorrect, as shown by Bell and Gough (Earth and Planetary Science Letters, 45, 475-482, 1979) and since acknowledged by Babcock. The second and third paragraphs under the heading "Stress Patterns" are accurate, but the last paragraph on page 9 again shows a misunderstanding by Dr Greggs. The regional stresses are sufficient to cause the fractures called breakouts, in the walls of oil-wells, only because the stress difference is greatly magnified by the well cavity (Gough and Bell, Canadian Journal of Earth Sciences, 19, 1358-1370, 1982). In the rock generally, the stress levels are low and the probability of movement on any faults, under these stresses, is small. The greater horizontal stress, S_H, lies in a range from slightly greater than to slightly less than the vertical stress, S_V, through the sedimentary basin (Woodland and Bell, in press 1989). S_V is essentially the overburden pressure due to the weight of overlying rock. Such a stress field indicates very low levels of tectonic activity and of seismic risk. This is in general agreement with the very low seismicity in Alberta (Plate 2 and pages 18-19, Seismicity Study, 1985).

There is a further point of importance regarding the stress field. In Alberta east of the Rocky Mountains, S_H is known to be directed NE-SW (Gough & Bell, Canadian Journal of Earth Sciences, 18, 638-645, 1981). The Greggs Report has this right. Such a stress field cannot produce motion on vertical faults aligned either NW-SE or NE-SW, because there is zero shear stress across faults in these alignments. Supposing that the faults shown in the Greggs Report do exist, the known stress field has an orientation that precludes slip on them, and produces maximum safety of such faults.

Both in magnitude and orientation, the known stress field in the region makes movement on NW-SE or NE-SW faults very improbable, assuming such faults to exist.

5. On page 4, in the Executive Summary of the Greggs Report, there is a suggestion that "jiggling" movements on faults may have the potential for risk to public safety. For reasons given in my comments 1 through 4, I see no evidence of such "jiggling" movements and no reason to expect such movements in the project area. That being so, I see no reason for concern about public safety arising from activation of faults by the dam project, and good reason to question the propriety of raising public alarm.

Yours truly,

D. Ian Gough.

D. Ian Gough M.Sc., Ph.D., F.R.S.C., F.A.G.U.
Professor Emeritus

APPENDIX A4

Dr. J.D. Mollard, P.Eng., P.Geol.

Dr. J.D. Mollard prepared a preliminary regional geology report for the Oldman River Dam Project that provided input on reservoir geology and erosion to Stanley Associates Engineering Ltd. and their sub-consultant Klohn Leonoff Ltd. Dr. Mollard obtained a B.E. in civil engineering from the University of Sakatchewan in 1945, an M.S. from Purdue University in 1947 and a Ph.D. from Cornell University in 1952. Since 1947 he has mapped engineering and geology features and conditions on over 60 embankment dam sites investigated in Canada. More than half of them have gone on to construction. He began mapping photolineaments for dam site investigations in 1947 and for the petroleum industry in 1957. Recently he published a review and application paper on the subject.

OLDMAN RIVER DAM PROJECT

FINAL COMMENT ON GREGGS' PRELIMINARY STRUCTURAL GEOLOGY REPORT DATED FEBRUARY 1989

Prepared for:

Mr. D. B. Chalcroft, P.Eng.
and
Mr. B. L. Baggott, P.Eng.
UMA Engineering Ltd.
in association with
Acres International Limited
17007-107 Avenue
Edmonton, Alberta
T5S 1G3

June, 1989

Prepared by:

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Dr. J. D. Mollard, P. Eng., P. Geol.

Dr. J. D. Mollard prepared a preliminary regional geology report for the Oldman River Dam Project that provided input on reservoir geology and erosion to Stanley Associates Engineering Ltd. and to their subconsultant Klohn Leonoff Ltd. Dr. Mollard obtained a B.E. in civil engineering from the University of Saskatchewan in 1945, an M.S. from Purdue University in 1947, and Ph.D. from Cornell University in 1952. Since 1947 he has mapped engineering geology features and conditions on over 60 embankment dam sites investigated in Canada. More than half of them have gone on to construction. He began mapping photolineaments for dam site investigations in 1947 and the petroleum industry in 1957, and has recently published a review and application paper on the subject.

OLDMAN RIVER DAM PROJECT
COMMENT ON GREGGS' PRELIMINARY STRUCTURAL GEOLOGY REPORT DATED FEBRUARY 1989

As a 1985 consultant on geological aspects of the Oldman River Dam reservoir I have been asked to review Greggs' February 1989 report and to comment on where I agree and disagree with the evidence presented, documenting my reasons so far as possible.

In doing this I am reminded of the role of an engineering geologist offering advice and guidance to the engineers designing dams and related works. I follow the recommendations of Drs. Berkey and Terzaghi (Figure 1). Dr. Berkey was an eminent engineering geologist. Dr. Terzaghi, a world renowned civil engineer and engineering geologist, is the founder of modern geotechnical engineering. A large part of their professional careers was devoted to geology applied to the investigation, design and construction of major engineering structures, and their impact on public health and safety.

Drs. Berkey and Terzaghi say the geologist's role in major construction projects is to discover, map, and explain the geology. Geologists should warn the design engineer of geological features that he or she feel could involve potential risks. However, they must not assume the role of the engineer, who alone is responsible for the design and safety of the dam and related structures.

Dr. Greggs' preliminary evaluation report appears to me to be an independent assessment of bedrock structure related to potential for risk and public safety created by construction of the Oldman River Dam Project. Because of this and because media coverage of Greggs' report appears to have generated concern that the dam might be unsafe, reference to the March 1989 University of Regina Basterfield Lecture by Professor Cohen may be of interest.

Speaking at the University of Regina in March 1989, Dr. Bernard L. Cohen, professor of physics at the University of Pittsburgh, delivered the annual Basterfield Lecture (Cohen, 1989). Criteria for the Basterfield Lecture deal with insights and authority of the impacts of science and technology on society.

The title of Dr. Cohen's topical March lecture was "Risk and Risk Aversion." Using a large number of overhead projection charts and tables, Cohen presented statistical data on a multitude of risks to public health and safety, including dam failure.

Dr. Cohen has written over 200 papers and several books, and is regarded as an international authority on life and property risk and risk reduction based on the analysis of available statistical data. Because of my interest in major construction projects and environmental concerns and constraints associated with them I asked Professor Cohen if he would send me reprints of a couple of his papers on risk statistics and some of his "overheads" (Cohen 1979, 1981, 1989).

During his address Dr. Cohen related potential for all human risk to loss of life expectancy, in seconds, minutes, hours, days, years, and decades. I found this concept interesting and easy to comprehend. Some of his statistics suggest that in the United States there is less risk of loss of life expectancy from dam failure than drinking coffee regularly, eating a tablespoon of peanut butter a day, or drinking a pint of milk a day.

On this subject I should say that I have spent more than 40 years investigating engineering geology features and conditions at sites of over 60 proposed embankment dams in Canada. Over half of them have been constructed; and as far as I know, they are all considered safe dams, with no reported casualties.

Replying to questions from the audience about media reporting on risks to human health and safety, which seemed to call in to question some of his statistics, Cohen said one should evaluate carefully media reports on human health and safety risks because they may appear out of context or be based on speculative information. Such reports may create unfounded fear and anxiety in the public mind. To illustrate this point he said a particularly controversial or contrary view opposed to a large body of informed opinion of specialists may receive undue emphasis and media attention. He drew diagrams on the blackboard to illustrate the point.

He went on to say that media reports on highly controversial issues can be a significant source of revenue since raising the Neilson TV rating by one point might generate a million dollars in advertising.

Coincidentally, Peter Gzowski gave the University of Regina annual lecture on journalism about a week after Dr. Cohen's lecture. We heard Gzowski stress, once again, the importance of fair and accurate media reporting on issues that are sensitive to public concern and anxiety. He said information that may seem unbiased and accurate to a reporter will often appear inaccurate and misleading to the person or agency being quoted. As a consequence, newspaper journalists and radio and TV persons reporting scientific and technical data, which are conceived to have a health or property risk, must be especially careful in reporting opposite or contentious points of view.

I found both lectures interesting. Some of the points discussed came to mind as I read Dr. Greggs' report, and again later when I learned of media reports relating to it.

My report follows an April 17-18, 1989 trip to the Oldman River Dam site and lower reservoir by a group of Project consultants, whose objective was to review geological features and concerns referred to in Greggs' February 1989 preliminary evaluation report of bedrock structures in the area.

My comments and discussion of Greggs' February 1989 report follow his headings, which appear below in boldface capital letters and underlined subheadings. I will comment on places where I agree or disagree with points raised in Greggs' report, especially as they relate to concerns about dam leakage and safety.

INTRODUCTION

The introduction deals with Greggs' specialty, the background information he obtained and assessed, and the focus of his report.

Dr. Robert Greggs was retained by Friends of the Oldman River to make a structural geology evaluation of bedrock conditions in the Oldman Dam site area. He is a retired professor of geology at Queen's University and, from my knowledge, has been consulting to the oil industry in Calgary in recent years. I am familiar with some of the research that Dr. Greggs has carried out on basement tectonism and his postulated fault block origin of Devonian reef evolution (Greggs and Greggs 1987).

I believe Dr. Greggs has given short courses to petroleum industry geologists on the effects of basement tectonism on faults in the overlying sedimentary rock succession. I also believe he has given courses on borehole core description and interpretation for oil exploration and petroleum reservoir exploitation assessment. As far as I know, Dr. Greggs is well received by oil industry geologists in Calgary.

I am not familiar with the documents listed in Greggs' Appendix I because I terminated my association with the Project in June 1985, shortly after investigations were begun.

My interim and preliminary reports to Klohn Leonoff Consultants in the spring and early summer of 1985 dealt with glacial geology and surface deposits and conditions around the reservoir rim -- not specifically with the dam site itself, although the dam is located on the reservoir rim. Because my preliminary report dealt with the regional geology around the reservoir, it contained photocopied portions of available bedrock geology maps. These maps show thrust faults in the upper Oldman River reservoir area, but no thrust or vertical faults in the lower reservoir and Oldman River Dam areas. My report also showed the general east-west trending locations of buried river valleys (Mollard 1985 -- Figures 6, 7 and 8).

Literature references in Greggs' report appear to relate mainly to basement tectonics and deep fracture networks, and to their significance in oil and gas exploration and production. They have not been referred to in the geological investigations of dam sites that I have been associated with. I have not seen the Hardy-BBT Ltd report referred to in Appendix I, so I cannot comment on it.

I do not know the extent of field work Dr. Greggs carried out in the Oldman River Dam site and lower reservoir areas. He points out his evaluation is preliminary in nature, and that more study beyond the scope of his present report is required. Also, there is no reference to his having had meetings with site geologists and engineers or their consultants.

It appears Dr. Greggs was unfamiliar with the geological and related engineering studies undertaken in the Oldman Dam site area over the period 1985-89. This information is important because Greggs was not part of the dam site geology investigation or the engineering design team that make use of geological data. Therefore he did not have the benefit of discussions at meetings where geological concerns are brought forward and evaluated by geologists and dam engineering design specialists, including the UMA/Acres Technical Review Committee and the Project Review Board consultants, among others.

I believe the UMA/Acres Technical Review Committee and the Project Review Board consultants on the Oldman River Dam Project (Messrs. Libby, Milligan, Klohn, Ringheim, Eckenfelder, among others), as well as other specialist consultants associated with the Project, are knowledgeable, competent and experienced in asessing the significance of structural geology features at major earth dam sites.

I suspect Dr. Greggs may be unaware of the background and experience of the engineering geologists, geophysicists, earth physicists and dam design engineers who have the responsibility for investigating and evaluating Oldman River Dam Project geological and geophysical data. Together their accumulated experience on domestic and international dam projects totals many hundreds of years.

EXECUTIVE SUMMARY

Dr. Greggs says: "Preliminary indications are that site stability and leakage problems are likely to arise due to the presence of vertical faults within the Oldman River Dam Project Area." In this connection I am attaching four figures photocopied from my June 1985 report (Figures 2 to 5). I have added eight other figures relating to points raised in Greggs' report (Figures 6 to 13).

Figures 2 to 5 have been photocopied from my 1985 preliminary geology report on the Oldman River Dam reservoir. Figure 6 was photocopied from Irish's map on the bedrock structure and rock types in the Oldman River Dam and lower reservoir areas. None of these maps show major regional vertical faults in the dam and lower reservoir area.

Figures 7 and 8 are portions of bedrock geology maps showing the locations of earth dams and reservoirs constructed several decades ago on faulted sedimentary rock strata in southwestern and west-central Alberta. If one examines the locations of thrust faults appearing on bedrock geology maps of the Waterton Dam area (Figure 7, after Douglas 1957) and the Ghost Dam area (Figure 8,after Ollerenshaw, 1975), and compares them with bedrock geology maps that show neither thrust faults nor vertical faults in the Oldman River Dam site area and lower reservoir area (Figures 2 to 6), one might conclude that the dams constructed many years ago at the Waterton and Ghost dam sites would be more unsafe from the standpoint of faults -- and would be more likely to leak from fractures in the bedrock -- than a dam constructed at the Oldman River Dam site.

Figure 9 (top) shows a dam constructed in the late 1940s and early 1950s, where I mapped photolineaments and where a large amount of grouting of open bedrock joints was carried out to control leakage through the dam abutments. Figures 9 (bottom) and 10 are airphoto stereograms showing the dam sites in Figures 7 and 8, respectively. The stereograms were prepared many years ago for classroom discussion of engineering geology features at earth dams constructed on fractured sedimentary bedrock in southwestern and west-central Alberta.

Figure 11 shows an embankment dam constructed near Estevan in the late 1950s. I carried out preliminary engineering geology investigations at the dam site. The geotechnical paper referenced in Figure 11 was published in 1973, and contains diagrams that illustrate the effects of Holocene valley erosion and rebound. Geological effects illustrated in Figure 11 are similar to those I believe to have occurred at the Oldman River Dam site, and that can result in brecciation, slickensides, and fractures produced by subhorizontal bedding plane shears.

Figure 12 shows the dominant trends of photolineaments and of local field mapped joint arrays surrounding the Oldman River Dam site. Linear trends shown on Figure 12 demonstrate a reasonable correlation between local and regional photolineament set trends on the one hand and local joint sets at the Oldman River Dam site on the other (see, also, Hodgson 1977 and Mollard 1989).

Although the trajectories of preferred joint sets and dominant photolineament sets may appear to be geometrically and genetically linked (Figure 12), in my view an individual surface lineament may or may not reflect directly underlying fault structures in the Precambrian basement rock or in the overlying sedimentary rock succession.

Thus I question that the traces of faults in rocks at and near the surface can be precisely located from the pattern and trends of surface lineament sets and joint sets in Figure 12 without confirming visual evidence of faults in the field, or, alternatively, without correlation with reasonably detailed subsurface geological and geophysical data.

Joints occur in all rocks of all ages. They include systematic as well as nonsystematic joints, and there is still no general agreement on the origin of regional joint systems (Nelson 1985, Stauffer and Gendzwill 1987, Hodgson 1988). Nelson (1985) distinguishes between tectonic fractures related to folding and faulting and regional fractures related mainly to systematic joints. He says (p. 17) that the origin of regional fractures is obscure. Like Stauffer and Gendzwill (1987) and Hodgson (1988), Nelson says that many theories have been proposed by geologists, but there is often little agreement among them.

In my opinion joints are extension (tension) cracks, not shear displacements. They tend to be more open at and near ground surface than at depth; and in my experience they often become less frequent and tighter (i.e. less permeable) at depths of around 100 m or so.

I believe crustal deformations -- including isostatic uplift, differential erosion-rebound, and warping -- that take place after joint initiation and formation can produce microfaults. In the Alberta foothills and adjoining plains the estimated depth of Tertiary and Mesozoic sediment erosion varies from about 2000 to 9000 m (quoted in Woodland

and Bell 1988). Because regional joint systems tend to be emplaced early in the history of sedimentary rocks, when these sediments are still poorly lithified and tensile strengths are low, a large amount of warping attending differential uplift or sediment removal and differential rebound can be expected to produce extension that develops additional joints as well as microfaults along pre-existing extension joints (Mollard 1989).

The geological age of faults (as well as the lack of mapped faults) is important in relation to the design life of an earth dam and associated reservoir. For this reason I have included a chart showing the age of the Tertiary Porcupine Hills Formation, which underlies the Oldman River Dam site and lower reservoir areas (Figure 13). This figure (from AGAT Laboratories 1987) indicates that the age of the sedimentary rock strata under the Oldman River Dam site are older than 57,800,000 years.

I agree with Greggs' first sentence in paragraph 3 on page 4. There is a good deal of support for a contemporary NE-SW maximum compressive stress orientation (Bell and Gough 1979, Gough and Bell 1981, Bell and Babcock 1986, Adams 1987, Mollard 1986b and 1988).

Greggs says that: "Preliminary assessment indicates that a minimum of five faults crosscut the dam and reservoir area." My observations do not indicate major regional vertical faults in the Porcupine Hills Formation at the

Oldman River Dam site area. The five fault locations shown on Figure 1 in Greggs' report do not appear on bedrock geology maps from which Figures 2 to 6, attached, were photocopied.

I expect dam design engineers are unfamiliar with the term "jiggling movement" (page 4, paragraph 4). In any event they will want to know more detail, inclduing the following: How intermittent are the movements in terms of decades, centuries, millenia, etc.? What are their magnitudes? Are the jiggling movements a response to cyclic or noncyclic stresses, which are likely to occur below all dams constructed on fractured sedimentary rocks in western Alberta. Are they caused by microseisms, distant earthquakes, local microearthquakes, earth tides, etc.? Are the movements slow isostatic rebound adjustment related to preglacial erosion or glacier melting and unloading (i.e. deglaciation)?

Greggs suggests that such movements could adversely affect the stability of any construction, such as the dam, dyke or spillway. It seems to me that such small movements will be common to all the dams constructed in western Alberta in similar geographic, geologic, or physiographic settings.

I do not think dam design engineers consider the occurrence and trends of deep basement faults and the possibility of movement along them unless potentially damaging seismotectonic activity is indicated in the record of past earthquakes. On the other hand, geologic time-scale adjustments along basement faults, and their effect on overlying strata, may be significant when exploring for or producing from oil and gas reservoirs hundreds of million years old (Sikabonyi 1957, Sikabonyi and Rodgers 1959, Martin 1967, Barss et al. 1970, Hrishevich 1970 and 1976, Jones 1980).

I believe bedrock strata below the Oldman River bed may or may not be more extensively fractured than rocks underlying the neighboring upland (page 4, paragraph 5). This depends on many factors. In order to assess it properly requires detailed examination of rock cores from the river bed, or examination of bedrock exposures in the river bed. As noted previously, sedimentary rocks at all depths and of all ages contain joint fractures. They tend to be the most common geologic structure at dams constructed on bedrock foundations, regardless of rock type or origin.

METHODOLOGY

Stauffer and Gendzwill (1987) discuss the possibility of a link between the orientations of trends in a pervasive orthogonal joint system in Quaternary sediments and exposed Tertiary and Mesozoic sedimentary rocks in the northern plains on the one hand, and the orientation of plate tectonic driving stresses in midcontinent North America.

Indicated maxima orthogonal joint trends are about N50°E and N40°W, corresponding well with the indicated regional stress field.

I have mapped a large number of photolineaments in the Oldman River Dam Project area and have compared their dominant trends with those mapped over a much larger region on the Canadian Prairies (Figure 12). In spite of an apparent correlation between photolineament set maxima and suborthogonal joint system directions at the Oldman River Dam site, in the absence of visible evidence of major regional vertical faults in exposed bedrock, or the absence of confirmatory subsurface geological and geophysical data, I believe specific locations of faults inferred from surface lineament evidence alone (e.g. topographic maps, airphotos, satellite images) must be considered speculative and remain to be established.

Geological map data in the Russell and Landes 1940 paper does not provide supporting evidence for major regional vertical faulting in the Oldman River Dam site and lower reservoir area. Their maps (565A, 566A and 567A) cover the Lethbridge-Medicine Hat area rather than the Oldman River Dam and lower reservoir area, and indicate that faults in exposed rocks in the region they mapped are virtually non-existent (see, also, Figures 2 to 6).

Site geologists logging borehole cores at all dam sites founded on bedrock routinely identify slickensides, brecciation, percent lost core, fractures, loss of circulation, hole caving, etc. This information is given to dam design engineers, who in turn consider pertinent core structure detail in their engineering design.

From what I have seen, the subhorizontal slickensides, brecciation, shears, and microfractures reported on Project data sheets at the Oldman River Dam result from bedding plane shear movements along relatively flat-lying rock seams that are thin and weak, and do not result from vertical fault movements, as Greggs seems to have inferred.

GEOLOGICAL BACKGROUND

The material on pages 7 and 8 is well documented in the literature, and I tend to agree with several points (Blanchet 1957; Mollard 1957, 1986b, 1989; Ozoray 1972; Babcock 1973). In my view, however, paleotectonic effects on sedimentation and deep structures apply much more to oil and gas exploration and to petroleum reservoir assessment and exploitation than to the engineering design of earth dams and their safety.

On page 9, paragraph 2, the roles of S_V and S_{Hmax} (the vertical principal stress and the maximum horizontal compressive stress) in fault activity are discussed. If one assumes that the contemporary regional maximum horizontal stress trajectory S_{Hmax} (maximum horizontal compressive stress; see Woodland and Bell 1988) is oriented precisely N45°E, there is no corresponding shear stress on faults oriented N45°E and N45°W. Even if S_{Hmax} were oriented somewhere between N50° and 70°E (Mollard 1986b, Adams 1987), considering the indicated relatively low in-situ regional deviatoric stress (Stauffer and Gendzwill 1987, Table 2; Woodland and Bell 1988, p.67-4 and Figure 2), the resulting shear stresses on Greggs' N45°E and N45°W oriented faults would be low.

Measured S_{Hmax} was higher than S_V in hard Cretaceous shale back from the South Saskatchewan River at Gardiner Dam, where photolineaments were identified in the late 1940s and early 1950s (Mollard 1986a). Valley rebound movements have been related to deglaciation and valley downcutting, and thus to relief of crustal stresses at dam sites on the Prairies (Peterson 1958). Lateral yield of mudrocks in valley sides may also open pre-existing joint fractures, and thereby develop surface lineaments far back from valley sides (Mollard 1986a and 1989).

In a paper dated 1960 (Peterson et al. 1960), the authors state (p. 13) that at a near-surface pressure test section in hard Cretaceous shale, some 400 feet back from the South Saskatchewan River, the measured stresses indicate that the vertical pressure S_V is equal to 100% overburden, and that the horizontal pressure S_H parallel to the river is equal to 150% of S_V. Moreover, the authors point out that horizontal rebound in Cretaceous mudrocks at Gardiner Dam has been substantial.

At greater depths beneath the Rocky Mountain foothills and some adjacent areas the stress regime may be $S_{Hmax} > S_V > S_{Hmin}$ or even $S_{Hmax} > S_{Hmin} > S_V$ according to Woodland and Bell (1988, p. 67-5), resulting in lower permeability in the deeper subsurface reservoir rocks.

I expect specialist consultants responsible for geological and geophysical investigations at the Oldman River Dam Project will have considered the influence of regional stresses on seismicity and dam safety. They also should have evaluated the effects of horizontal shear displacement, as reported on borehole core description sheets and on records of joint fractures and other structural effects observed during tunnel and portal excavations.

Descriptions of borehole cores from the Oldman River Dam site should be reviewed with geologists making the core observations. Otherwise references to brecciation, slickensides, shears, fractures, etc., might be incorrectly assumed to refer to vertical faulting instead of horizontal shear displacements along bedding planes.

FAULT LOCATIONS

During my field observations in the spring of 1985, and again on April 17, 1989, I saw no evidence to confirm the existence of the crosscutting sets of five major regional vertical faults shown on Greggs' Figure 1.

On page 15 Dr. Greggs notes: "The best documentation for these faults is by seismic surveying (reflection, not refraction), and careful geological surface mapping."

Evidence for Specific Vertical Faults as Mapped

Figure 2 (Maughan and Perry 1986) and Figure 3 (Downey et al. 1987) show highly generalized megalineaments used to infer regional paleotectonic trends and thereby guide geological exploration programs in search of petroleum and mineral deposits. In my opinion, at the very small scale of these figures, the indicated trends should not be extended great distances to plot specific fault locations in southern Alberta. I assume Greggs included Figures 2 and 3 to demonstrate the existence of reported regionally pervasive NE-SW and NW-SE deep fracture systems in the Rocky Mountains and neighboring northern central plains region.

Faults A and B: I assume that these faults are speculative on the basis of what I have said. In my view they may or may not exist at depths considered of no significance by dam design engineers.

I believe faults C, X and Y locations are likewise speculative. They may or may not occur in basement rocks and in deeper sedimentary rock formations at the locations shown. Absolutely parallel faults trending at precisely N45°W and N45°E should, I think, be considered hypothetical. I would assume this may be the reason that they were shown at these precise orientations.

IMPLICATIONS FOR SITE STABILITY

In this section, Greggs suggests there is conclusive evidence for pervasive vertical faults based on the data provided and confirmatory field work. As mentioned above, I have been unable to confirm their existence from my studies. In the case of microfaults it is impossible to identify their true number and distribution, even at great time and cost. Most dam design engineers will assume the existence of systematic and nonsystematic joints (Hodgson 1988) as well as microfaults, and then design for their occurrence. I assume this has been done.

On a geological time scale I believe the possibility of independent fault block movements at depth may be so, as Greggs suggests. Again one should be reminded that no major regional vertical faults have been mapped in the Porcupine Hills Formation below the Oldman River Dam site and lower reservoir (Figures 2 to 6), in rocks that are more than 57,800,000 years old (AGAT Laboratories 1988).

During office and field investigations in the spring of 1985 it was my impression that seismotectonic activity in the dam and reservoir area would be addressed by specialist consultants -- either by seismologists, geophysicists, or earth physicists. I understand this has been done.

Referring to grouting of fractures in brittle rock, this seems to have worked satisfactorily at the St Mary Dam, where open joint fractures were grouted several decades ago. Considerable expertise relating to grouting around dam sites now exists in southwestern Alberta. Over a period of many years, engineers and geologists have worked on grouting programs at and near dam sites in southwestern Alberta (e.g. the St Mary and Waterton dam areas).

I do not believe that fluids injected into the San Andreas fault grease it. Rather, high pore fluid pressures reduces the effective stress. Some investigators postulate the San Andreas fault is a nearly frictionless interface in a region of high regional deviatoric stress (Mount and Suppe 1987).

RECOMMENDATIONS

From the evidence I have seen and discussions I have had with other consultants I am led to believe there is no justification for obtaining more information that now exists on faults, regional stress systems, seismicity, and earth movements on the Oldman River Dam Project.

From such discussions I also believe that the studies carried out to date have evaluated potential instabilities that might be caused by slaking mudrocks.

In my preliminary geology report in June 1985, which included photogeologic mapping, I identified roughly E-W trending photolineaments in the Oldman River Dam site area. I suggested they probably reflected master joint structure trends in bedrock (Figure 26, Mollard, June 19, 1985). Although photolineaments and regional jointing appear to be associated, there is no reason to conclude they represent specific fault locations unless this can be established from visual evidence in the field or from subsurface data.

GREGGS' CONCLUSIONS

In my opinion additional structural geology mapping is not warranted. Greggs says he believes the Oldman River Dam site may be structurally complex. I believe it to be structurally simple compared to other dam sites I have investigated from an engineering geology perspective.

Experienced dam geologists and engineers on the Project should be familiar with slaking mudrocks.

Geologic conditions at the Teton Dam, referred to by Greggs, are very different from those at the Oldman River Dam. At the Teton Dam the rocks exposed in steep canyon walls are intensely layered and jointed rhyolite with inclusions of basalt, breccia and welded ash-flow tuff -- all volcanic in origin. At the Oldman River Dam the rocks exposed in the valley walls are relatively undeformed, essentially flat-lying interbedded sedimentary rocks. The sources of impervious borrow available for construction and their geotechnical properties are also very different: windblown silt and sandy silt at the Teton Dam and clay till sediment at the Oldman Dam. There is little similarity in the geology of the bedrock and overburden deposits at these two sites (see Leps, 1988).

Concerns raised by Greggs are discussed frequently at consulting board meetings. Their significance is routinely reviewed by engineering geologists, geophysicists, geotechnical engineers, and civil design engineers.

It has been my experience that review consultants ask site geologists a large number of pointed and penetrating questions related to dam design for reasons of leakage and dam safety. The consultants in turn must satisfy themselves that all geological and seismic concerns have been properly assessed and considered in the design and construction of the Project. These considerations include potential faulting in dam foundation rocks.

SUMMARY OF J. D. MOLLARD OBSERVATIONS AND CONCLUSIONS

1. Several independently prepared bedrock geology maps show no evidence of major regional vertical faulting in the Oldman River Dam site and lower reservoir area, where the dam foundation and abutment bedrock is the Porcupine Hills Formation, a formation that is more than 57,800,000 years old.

2. My office airphoto studies and field examinations of bedrock in the Oldman River Dam site and lower reservoir area from 1985 to 1989 reveal systematic and nonsystematic joints and a few microfaults having a displacement of a few metres. These studies not show a pervasive system of major regional vertical faults in rocks underlying the dam and lower reservoir area.

3. The rock cores I have viewed, and the project data sheets describing them, refer to brecciation, slickensides, shears, minor fractures, etc. These structural features refer to subhorizontal bedding plane shears, not vertical faults. They are a common occurrence at dam sites founded on soft sedimentary rocks in the Western Canada Sedimentary Basin.

4. A contemporary NE-SW trending regional maximum horizontal compressive stress S_{Hmax}, which is likely around N50-60^{o}E, will develop relatively low shear stresses on the five indicated major regional faults that trend N45^{o}E and N45^{o}W (Bell and Gough 1979, Stauffer and Gendzwill 1987, Woodland and Bell 1988).

5. The geology of the intensely layered and jointed volcanic rocks at Teton Dam is very different from the geology of the relatively undeformed sedimentary bedrock at the Oldman River Dam.

6. Embankment dams have been constructed on fractured sedimentary rocks at the St Mary, Waterton, Bighorn, and Brazeau dams in the Rocky Mountain Foothills and adjoining plains of western Alberta. I have carried out geological investigations on all of them. To my knowledge these dams have operated successfully, and none have created a risk to public safety.

7. The team of Project consultants on the Oldman River Dam Project have several hundred years of combined experience on dam investigation, design and construction. This aggregate experience includes assessing the significance of a wide variety of geological features and conditions as well as seismicity as they influence the engineering design of embankment dams -- not only in western Canada but elsewhere in Canada and overseas as well.

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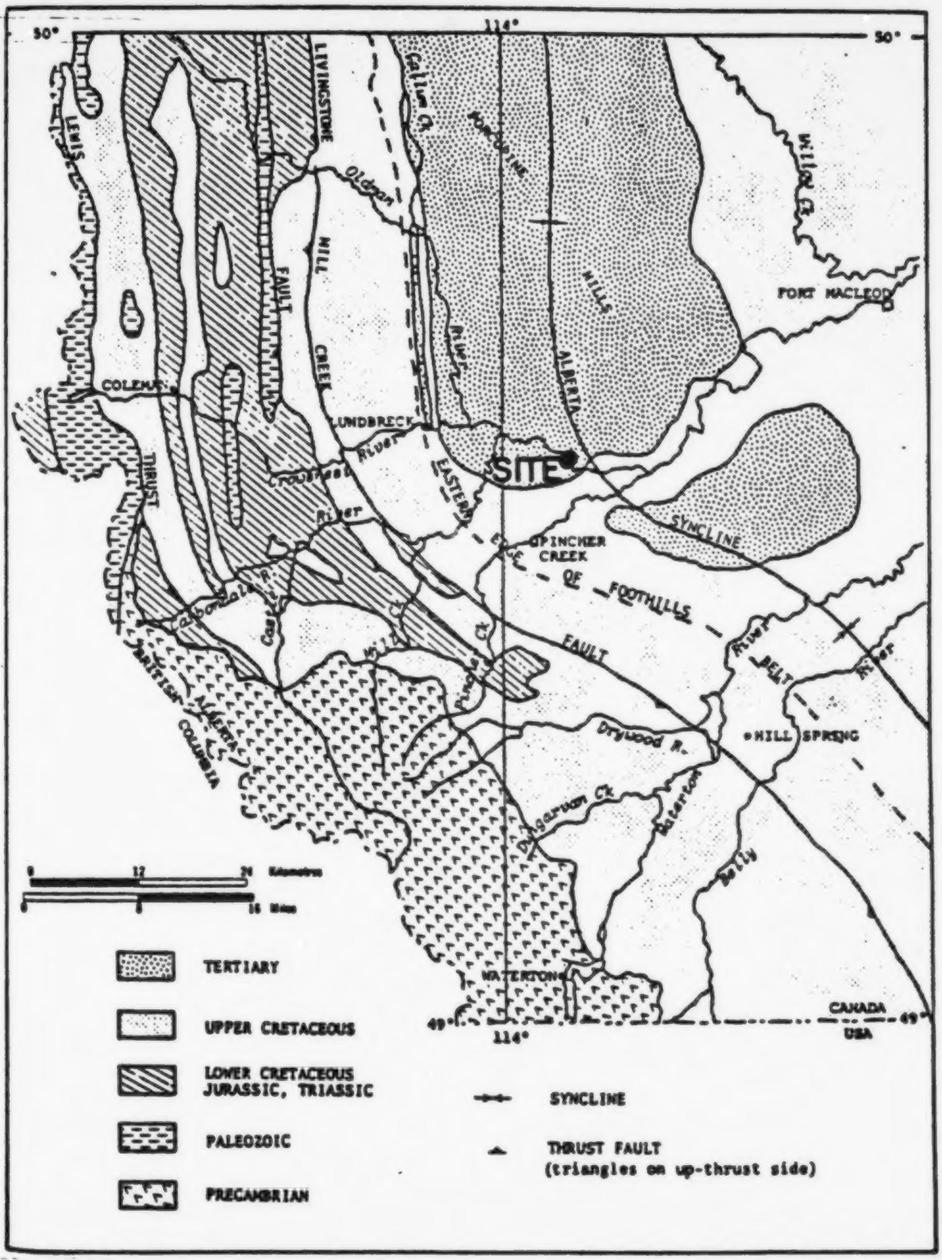
DR. TERZAGHI, WHO WAS FIRMLY AGAINST THE ENGINEERING GEOLOGIST ASSUMING ANY OF THE RESPONSIBILITIES OF THE ENGINEER, DREW ATTENTION TO THE WRITINGS OF DR. BERKEY, WHO IN 1929 DEFINED THE GEOLOGIST'S ROLE AS FOLLOWS:"IT IS HIS DUTY TO DISCOVER,WARN,EXPLAIN WITHOUT ASSUMING THE PARTICULAR RESPONSIBILITY OF THE ENGINEER WHO HAS TO DESIGN THE STRUCTURE AND DETERMINE HOW TO MEET ALL THE CONDITIONS PRESENTED AND STAND FORTH AS THE MAN RESPONSIBLE FOR THE PROJECT."

Excerpt from the theme lecture paper by John F. Gartner, P. Eng., engineering geologist and Chairman, Engineering Geology Division, Canadian Geotechnical Society. Paper delivered at the 41st Canadian Geotechnical Conference, October 5, 1988, Waterloo, Ontario.

Judging by this reference to Drs. Berkey and Terzaghi, the geologist has a duty to discover, warn, and explain geological information that he or she envisions would affect the exploration, design, and safety of a major civil work, such as a dam and reservoir -- this without assuming the responsibility of the engineer, who alone is the person responsible for the project, its design and safety. One should add that such discovery, warning and explanation is, of necessity, based on the geological data that is available to the geologist.

Figure 1

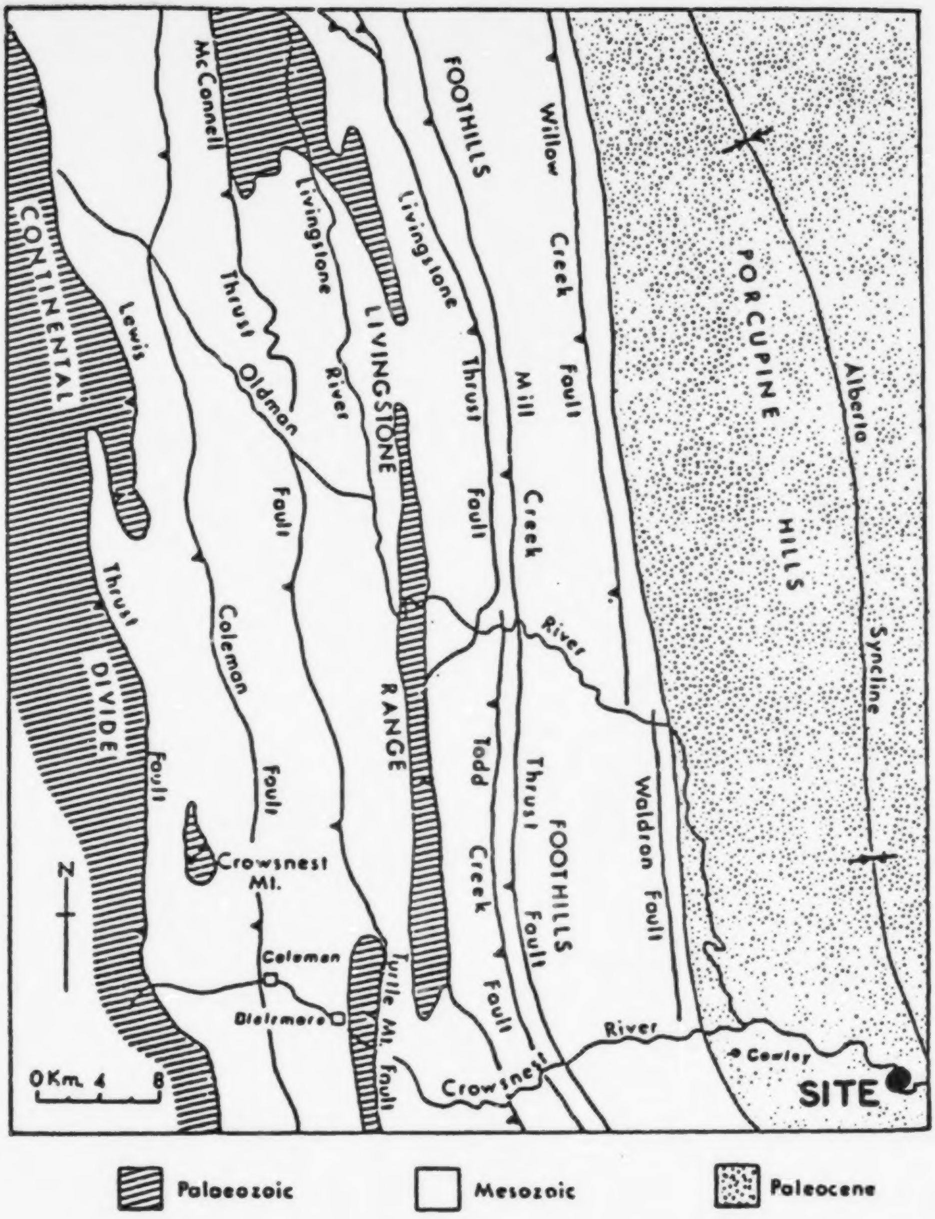

50°
114°
50°
LEWIS
LIVINGSTONE
Gallup Ck.
PORCUPINE
Oldman
Willow Ck.
HILLS
FORT MACLEOD
MILL
FAULT
CREEK
River
ALBERTA
COLEMAN
LUNDBRECK
SITE
Crowsnest River
THRUST
EASTERN
PINCHER CREEK
SYNCLINE
EDGE OF FOOTHILLS
FAULT
BELT
River
River
Carbondale R.
Castle
Mill
Pincher Ck.
BRITISH COLUMBIA
ALBERTA
Drywood R.
HILL SPRING
Dungarvan Ck.
Waterton
Belly
WATERTON
CANADA
USA
49°
114°
49°
0
12
24
Kilometres
0
8
16
Miles
TERTIARY
UPPER CRETACEOUS
LOWER CRETACEOUS JURASSIC, TRIASSIC
PALEOZOIC
PRECAMBRIAN
SYNCLINE
THRUST FAULT (triangles on up-thrust side)

Index map of southwestern Alberta showing general geologic features (modified after Henderson and Douglas, 1954, and Mellon, 1961).

(From Wall and Rosene, 1977.)

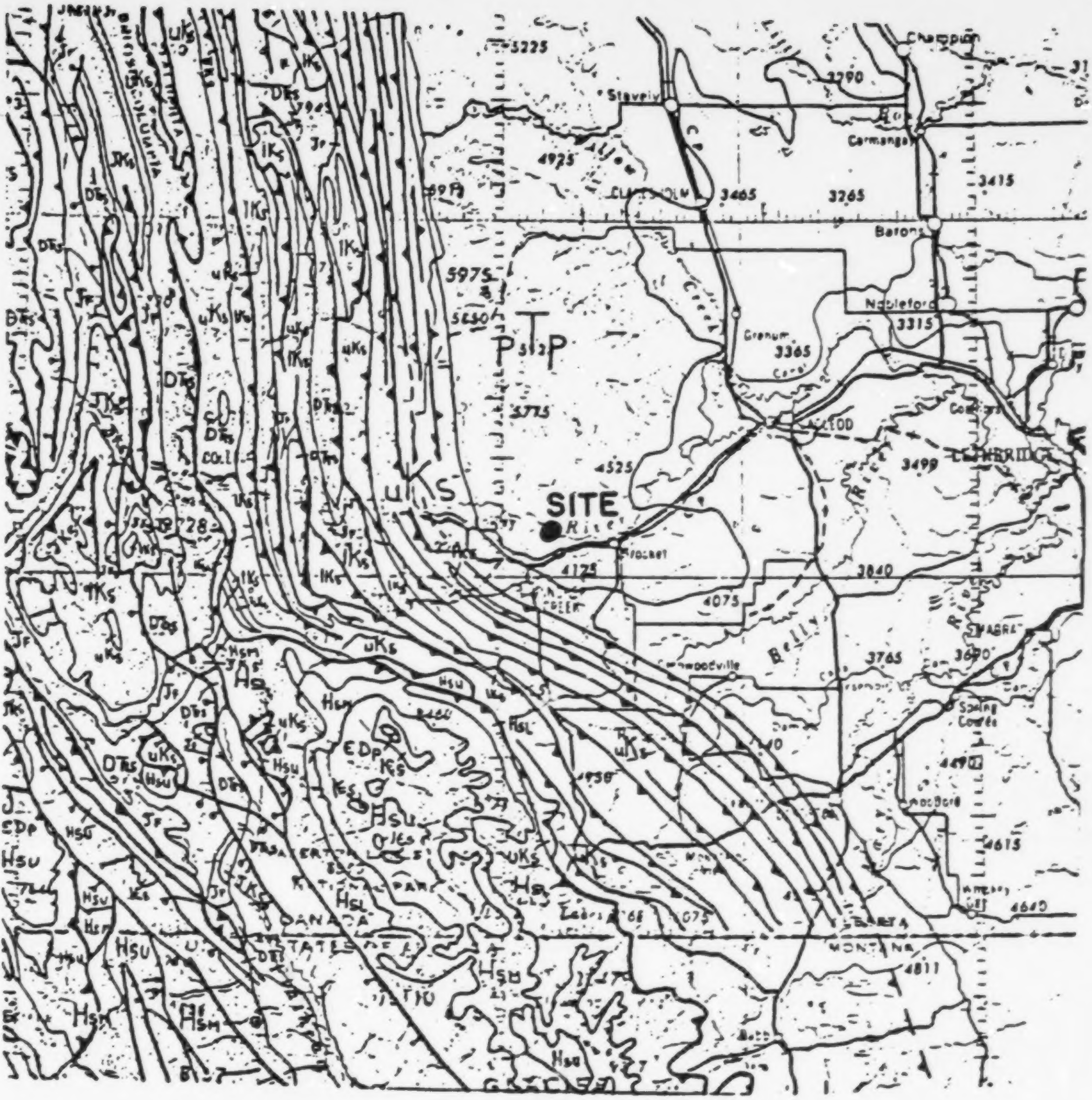
Regional bedrock geology of study area

Figure 2


CONTINENTAL DIVIDE
Lewis Thrust Fault
McConnell Thrust
Livingstone
Livingstone River
Oldman River
LIVINGSTONE RANGE
Coleman Fault
Livingstone Thrust Fault
FOOTHILLS
Willow Creek Fault
Mill Creek
Todd Creek Fault
Thrust Fault
FOOTHILLS
Waldron Fault
PORCUPINE HILLS
Alberta Syncline
Crowsnest Mt.
Coleman
Blairmore
Tuttle Mt. Fault
Crowsnest River
Cowley
SITE
N
0 Km. 4 8
Palaeozoic
Mesozoic
Paleocene

Generalized bedrock geology of the study area. Only the major faults are shown. A detailed description of the rock lithologies for the individual formations is given in Figure 5. (After Douglas, 1950; Norris, 1958a and b; and Price, 1962.)

Figure 3


SITE
pTp
uKs
lKs
Champion
Carmangay
Stavely
Claresholm
Barons
Nobleford
Granum
Macleod
Lethbridge
Pincher
Cardston
Belly
Waterton Lakes
ALBERTA
MONTANA
CANADA
UNITED STATES

PALEOCENE

pTp Sandstone, shale. PORCUPINE HILLS and PASKAPOO Fms.

CRETACEOUS

UPPER CRETACEOUS

uKs Sandstone, shale. ALBERTA Group; EDMONTON, BRAZEAU, BELLY R., WILLOW CK., ST. MARY R., BEARPAW, MILK R., KOOTENAI, etc. Fms.

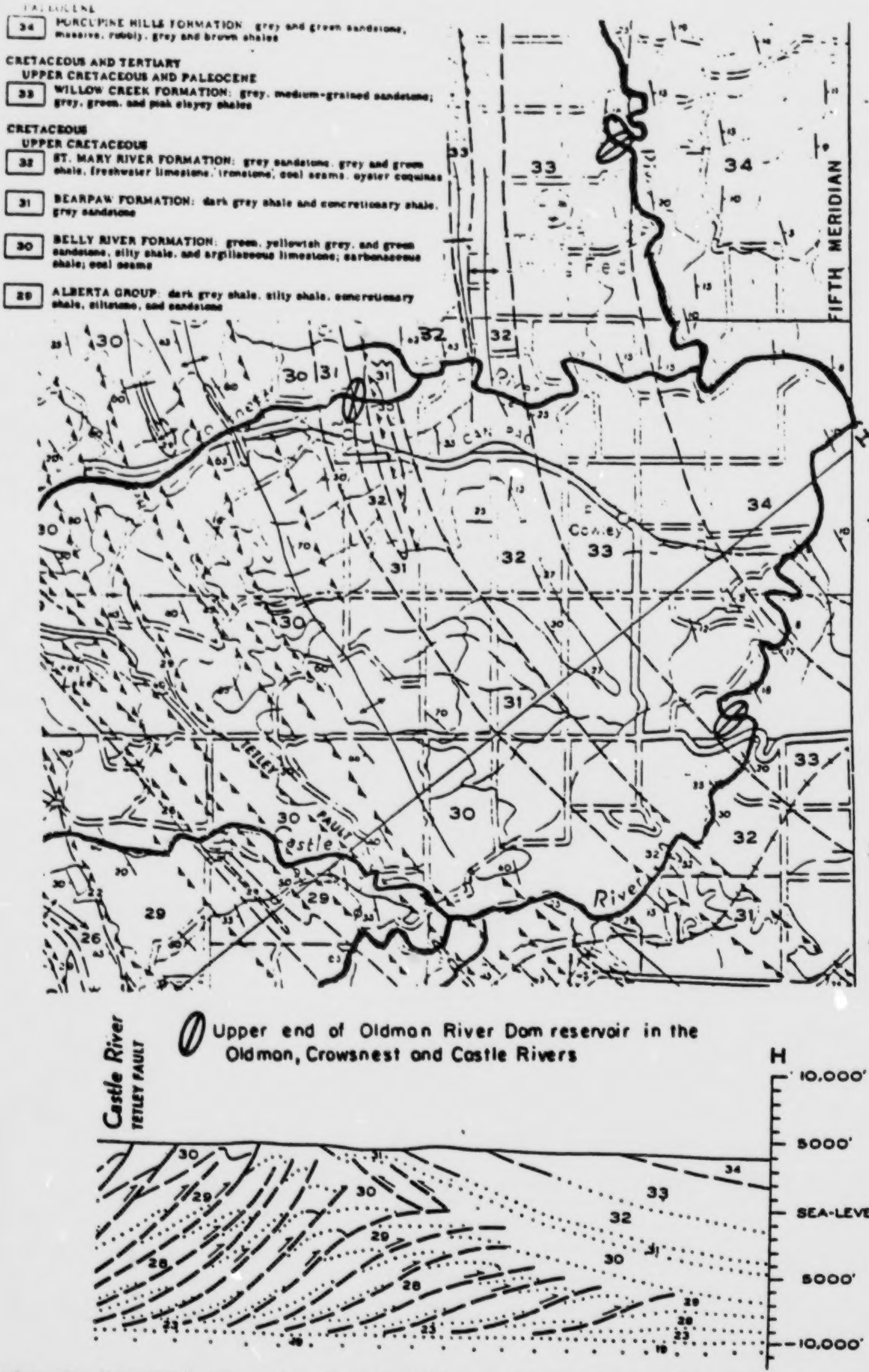
LOWER CRETACEOUS

lKs Sandstone, shale, coal, conglomerate, volcanic breccia. BLAIRMORE Group; CROWSNEST Fm.

(From Okulitch and Woodsworth, 1977.)

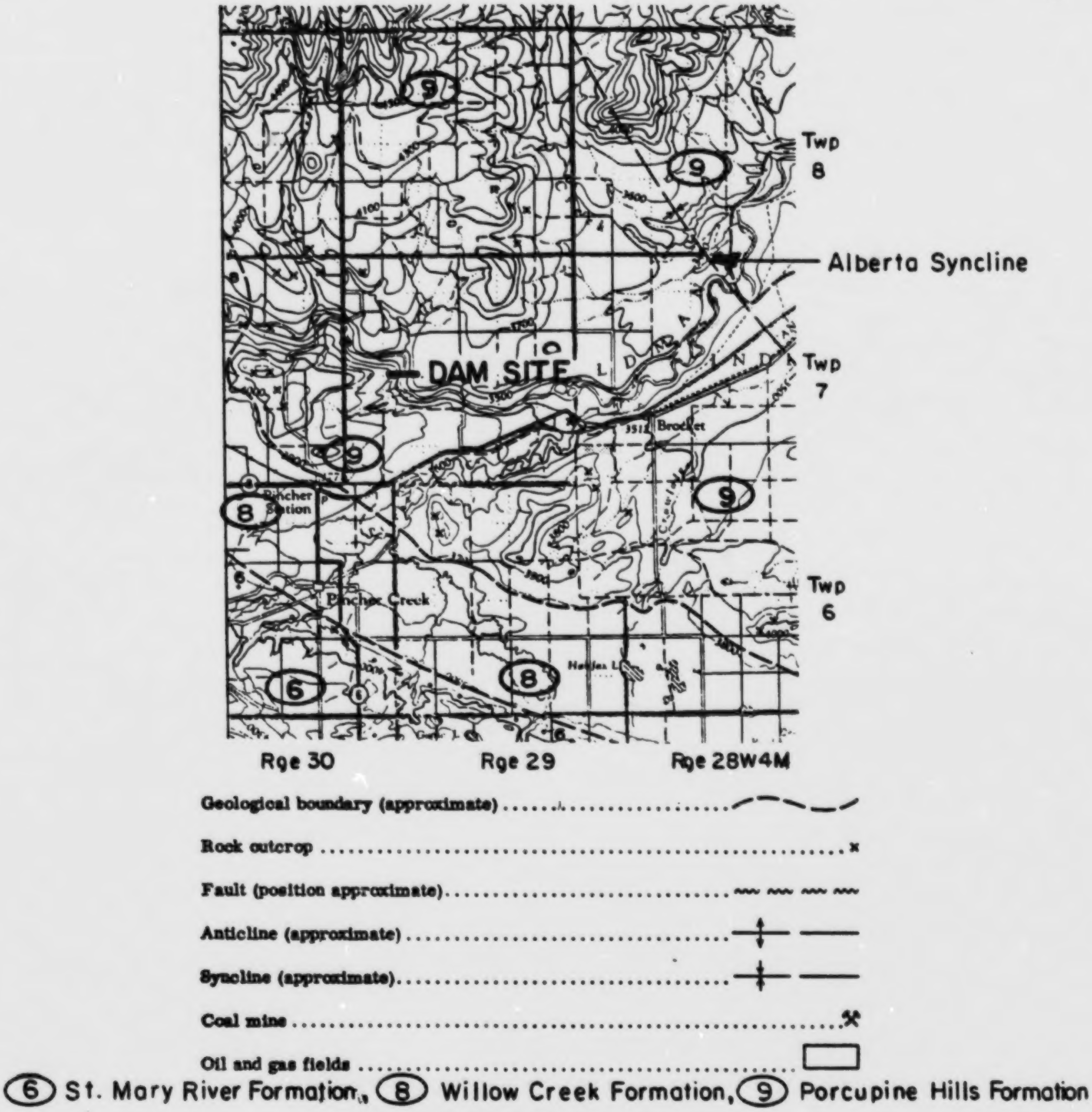
Bedrock geology map of
southwestern Alberta

Figure 4


PALEOCENE
34 PORCUPINE HILLS FORMATION grey and green sandstone, massive, rubbly, grey and brown shales
CRETACEOUS AND TERTIARY
UPPER CRETACEOUS AND PALEOCENE
33 WILLOW CREEK FORMATION: grey, medium-grained sandstone; grey, green, and pink clayey shales
CRETACEOUS
UPPER CRETACEOUS
32 ST. MARY RIVER FORMATION: grey sandstone, grey and green shale, freshwater limestone, ironstone, coal seams, oyster coquinas
31 BEARPAW FORMATION: dark grey shale and concretionary shale, grey sandstone
30 BELLY RIVER FORMATION: green, yellowish grey, and green sandstone, silty shale, and argillaceous limestone; carbonaceous shale; coal seams
29 ALBERTA GROUP: dark grey shale, silty shale, concretionary shale, siltstone, and sandstone
FIFTH MERIDIAN
Cowley
TETLEY FAULT
Castle River
H
Tp. 7
30'
Tp. 6
Upper end of Oldman River Dam reservoir in the Oldman, Crowsnest and Castle Rivers
Castle River
TETLEY FAULT
H
10,000'
5000'
SEA-LEVEL
5000'
-10,000'

Bedrock formations and structural geology of southwestern Alberta. (From R.A. Price, 1962.)

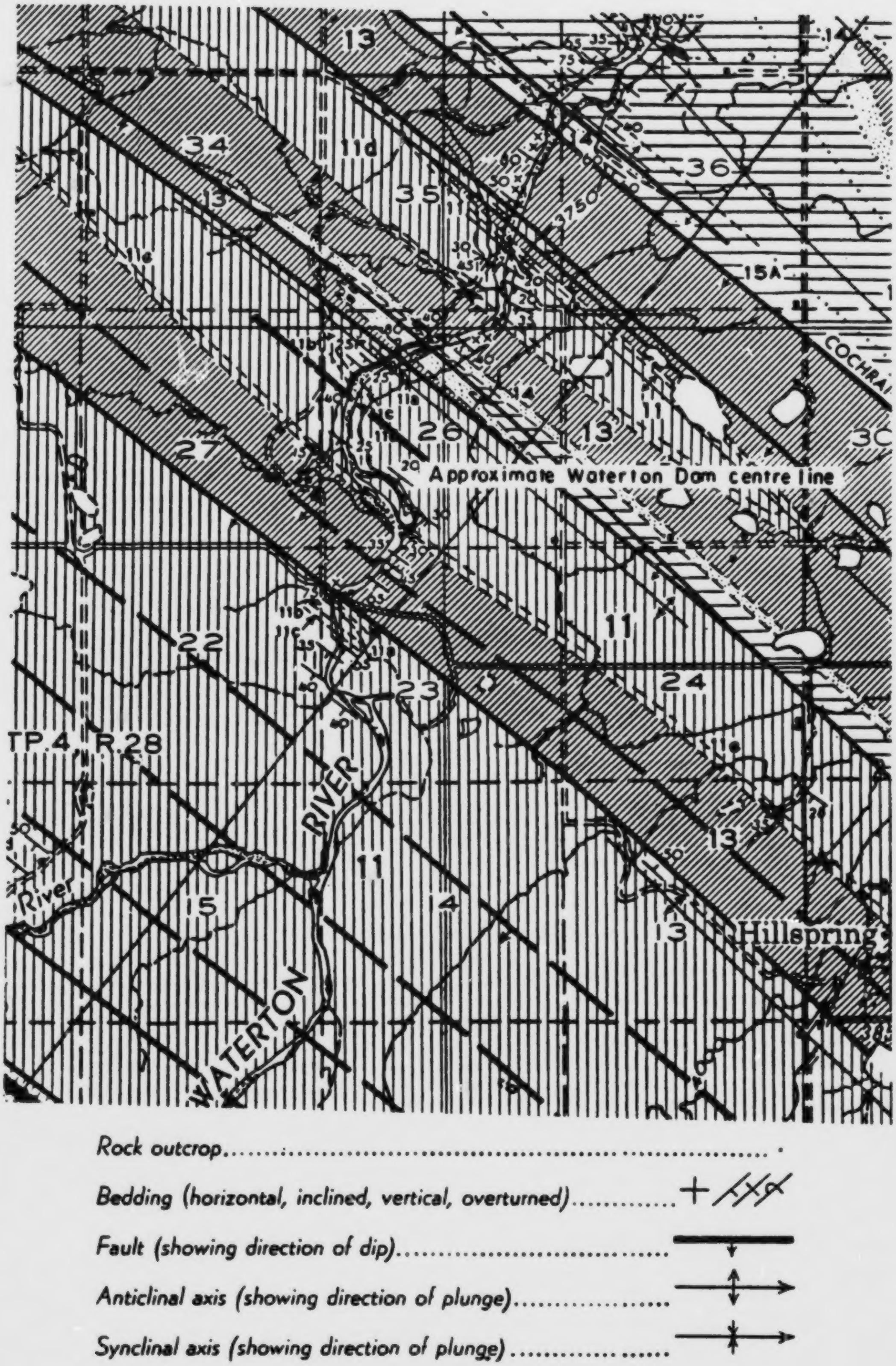
Figure 5


9
9
Twp
8
Alberta Syncline
DAM SITE
Twp
7
Brocket
9
Pincher
Station
8
9
Pincher Creek
Twp
6
6
8
Rge 30
Rge 29
Rge 28W4M
Geological boundary (approximate)
Rock outcrop
Fault (position approximate)
Anticline (approximate)
Syncline (approximate)
Coal mine
Oil and gas fields
⑥ St. Mary River Formation, ⑧ Willow Creek Formation, ⑨ Porcupine Hills Formation

Geology by E.J.W. Irish, 1965, 1966, 1967

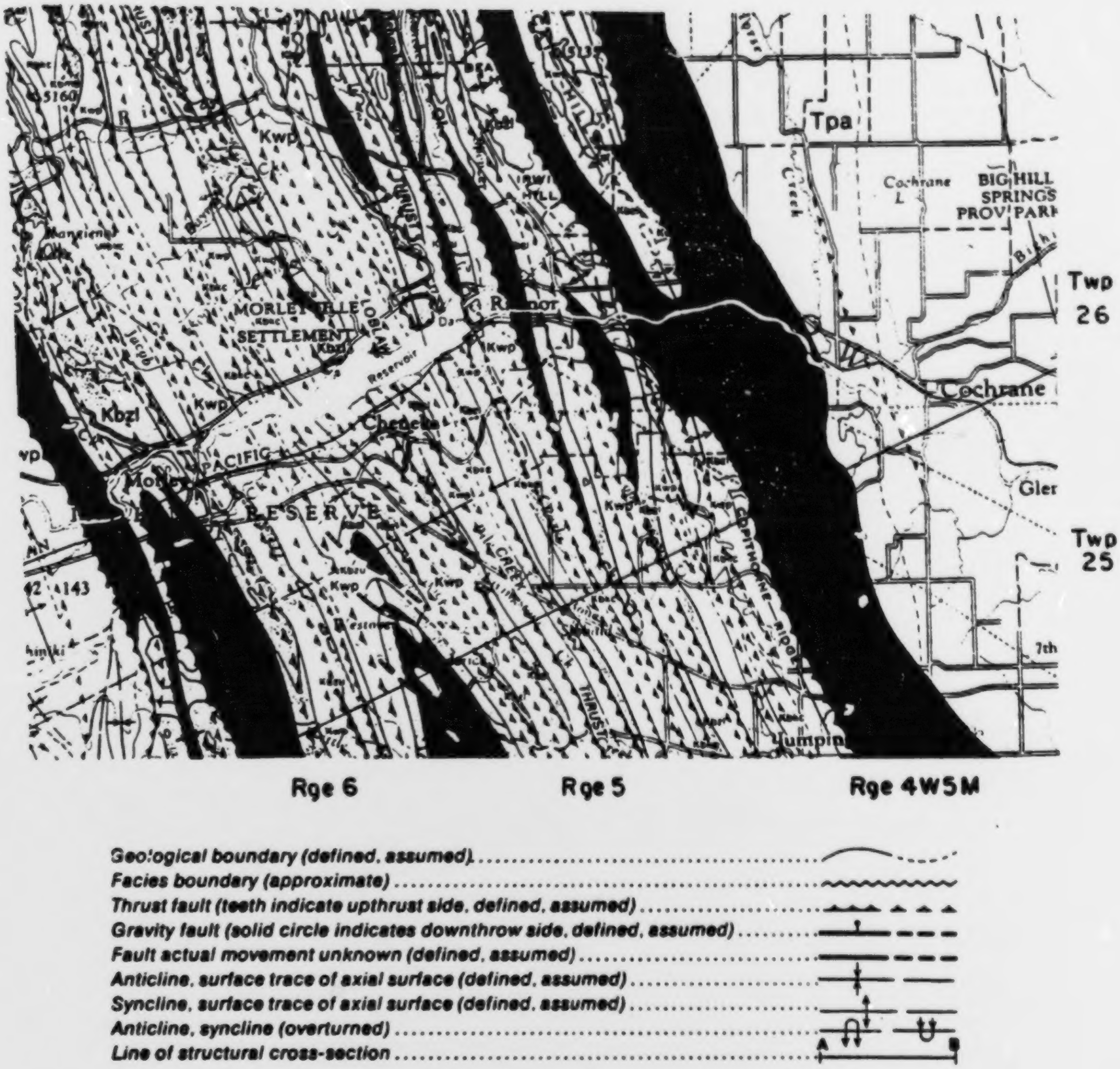
Oldman Dam site and indicated geological formation boundaries and structures (folds, faults). (From GSC Map 20-1967 by E.J.W. Irish.)

Figure 6


13
34
11d
35
36
15A
COCHRA
13
26
27
13
11
30
Approximate Waterton Dam centre line
22
11
23
24
TP.4 R.28
RIVER
River
11
15
4
13
Hillspring
WATERTON
Rock outcrop
Bedding (horizontal, inclined, vertical, overturned)
Fault (showing direction of dip)
Anticlinal axis (showing direction of plunge)
Synclinal axis (showing direction of plunge)

From GSC Preliminary Map 51-22, 1949, by R.J.W. Douglas.
The map shows bedrock structure in the Waterton Dam area.

Figure 7


Tpa
Kwp
Kbzl
Cochrane L
BIG HILL SPRINGS PROV PARK
Twp 26
Twp 25
MORLEYVILLE SETTLEMENT
Radnor
Reservoir
Chencka
PACIFIC
Morley
RESERVE
Cochrane
Glen
Creek
Jumpin
5160
4143
7th
Rge 6
Rge 5
Rge 4W5M
Geological boundary (defined, assumed)
Facies boundary (approximate)
Thrust fault (teeth indicate upthrust side, defined, assumed)
Gravity fault (solid circle indicates downthrow side, defined, assumed)
Fault actual movement unknown (defined, assumed)
Anticline, surface trace of axial surface (defined, assumed)
Syncline, surface trace of axial surface (defined, assumed)
Anticline, syncline (overturned)
Line of structural cross-section
A
B

Compilation by N.C. Ollerenshaw 1973-1975

Based on published maps of the Geological Survey of Canada and field work by N.C. Ollerenshaw, 1962-1971. See "Sources of Information"

Extensive faulting in the Ghost Dam area on the Bow River, west of Calgary.

Figure 8

Plate
XXV

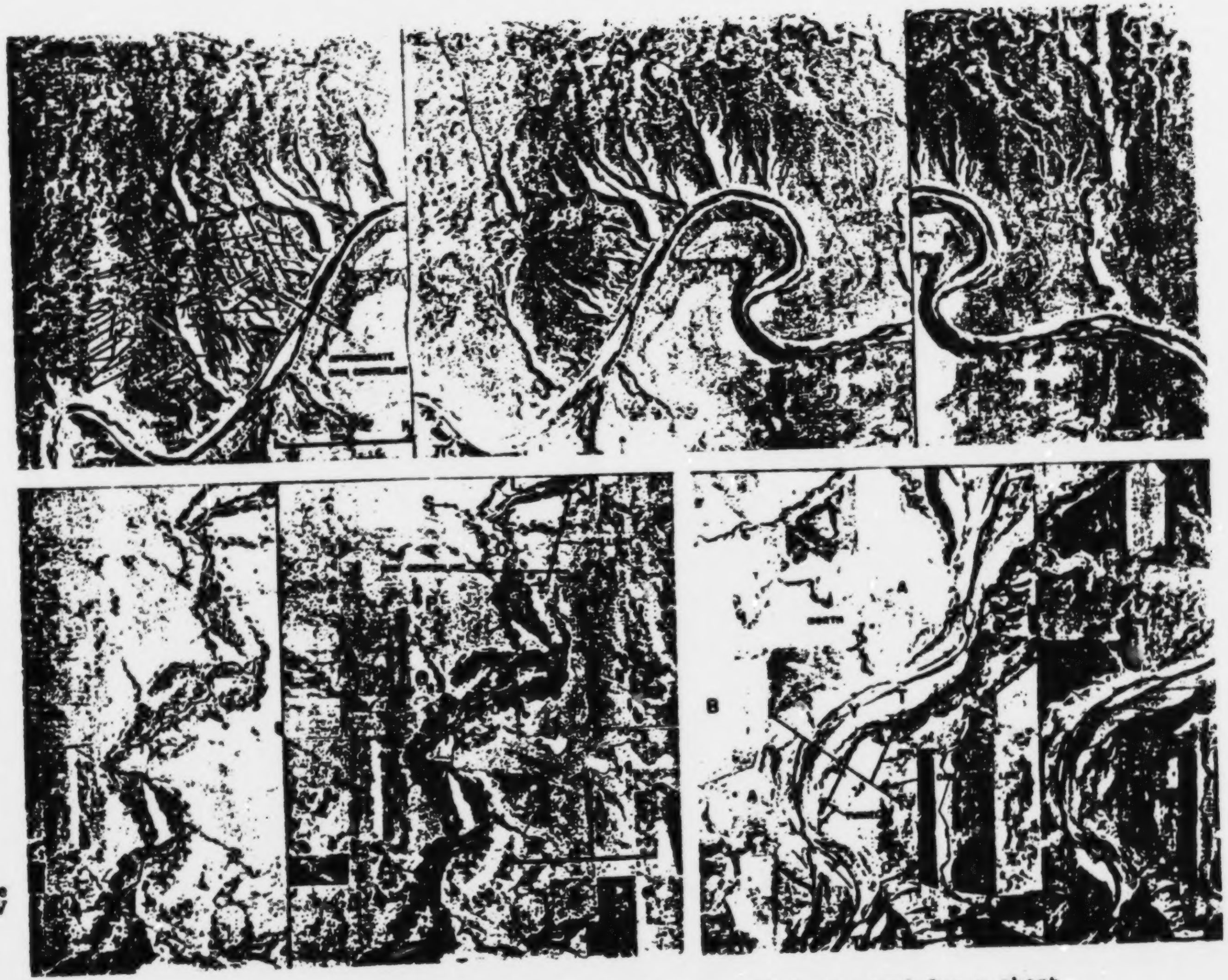


Plate XXV From a small airphoto interpretation laboratory manual I prepared for a short course to engineers and geologists, given at the University of Alberta in 1960. Top stereotriplet: St. Mary dam site before construction. Bottom left: Boundary dam site, Estevan, Saskatchewan, before construction. Bottom right: Waterton dam site before construction. Bedrock joints occur in the abutments at St Mary Dam. Bedrock joints and faults occur in vicinity of both the Boundary and Waterton dams. All dams are three or more decades old, and all three dams and reservoirs appear safe and serviceable. See Figure 7 for faults in the Waterton Dam area.

Figure 9

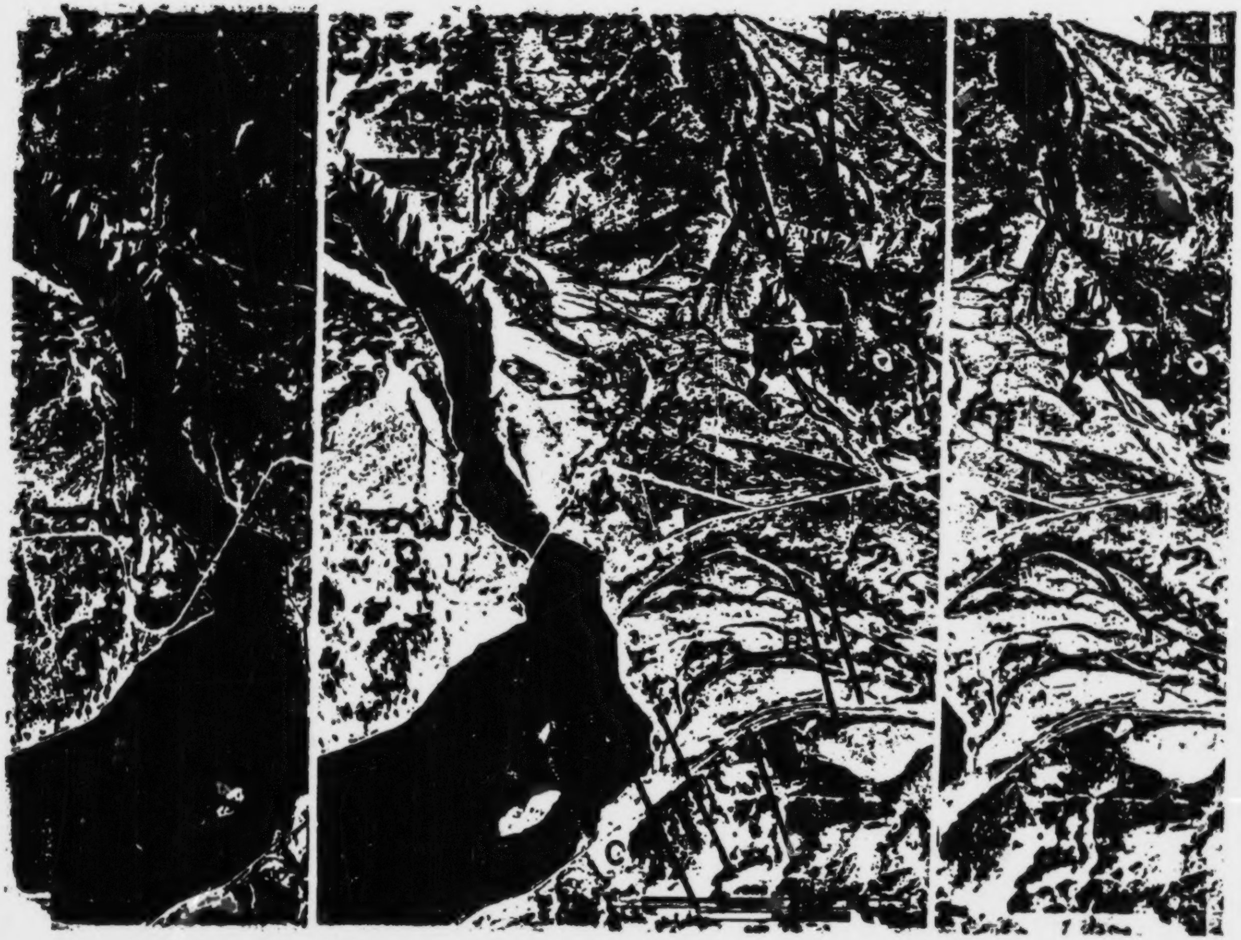
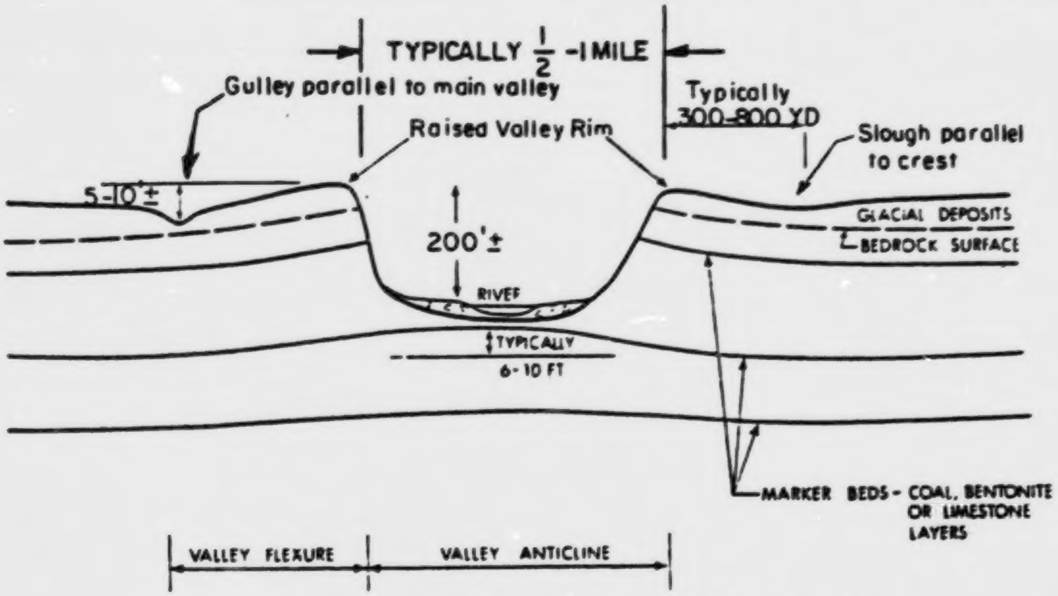
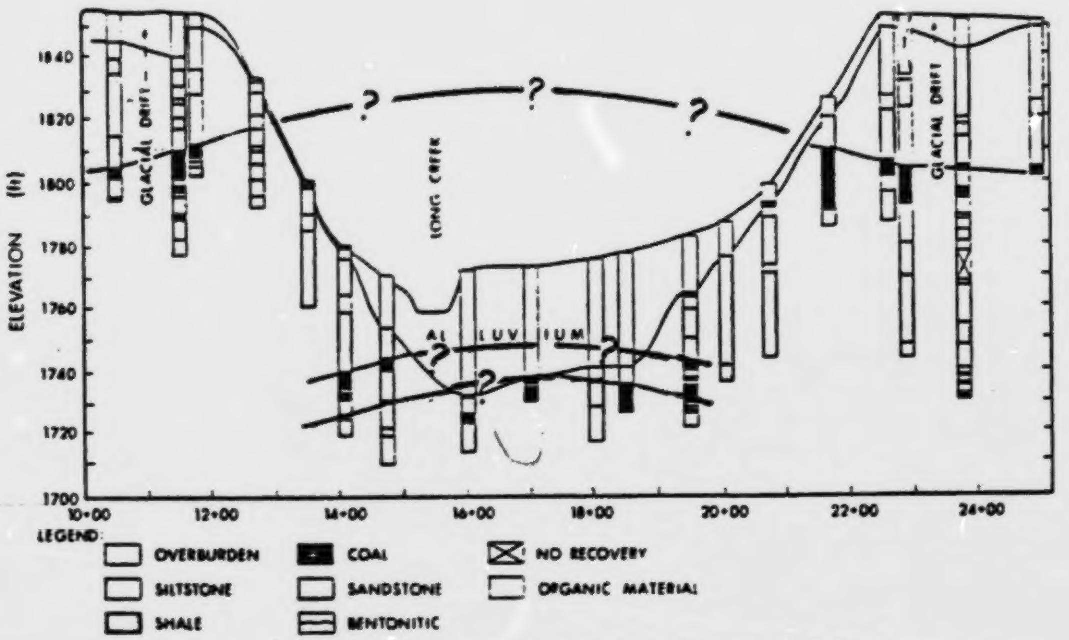


Plate 5.9 From my 1972 Airphoto Interpretation Manual containing 680 interpreted stereograms of landforms and surface materials in Canada. This stereotriplet shows airphoto-identifiable bedrock fracture traces at several locations at and near Ghost dam and reservoir (see locations A, B and C). Ghost Dam, probably subject to routine safety checks, appears safe and serviceable. Joints and faults (i.e. fractures) in bedrock are common at this and other embankment dams constructed on bedrock. Figure 8 shows extensive faulting in the Ghost Dam area.

Figure 10


TYPICALLY $\frac{1}{2}$ -1 MILE
Gulley parallel to main valley
Typically 300-800 YD
Raised Valley Rim
Slough parallel to crest
5-10'±
200'±
GLACIAL DEPOSITS
BEDROCK SURFACE
RIVER
TYPICALLY 6-10 FT
MARKER BEDS - COAL, BENTONITE OR LIMESTONE LAYERS
VALLEY FLEXURE
VALLEY ANTICLINE

Idealized section illustrating features resulting from valley rebound.


ELEVATION (ft)
1840
1820
1800
1780
1760
1740
1720
1700
10+00
12+00
14+00
16+00
18+00
20+00
22+00
24+00
GLACIAL DRIFT
LONG CREEK
ALLUVIUM
?
LEGEND:
OVERBURDEN
COAL
NO RECOVERY
SILTSTONE
SANDSTONE
ORGANIC MATERIAL
SHALE
BENTONITIC

Geologic profile at Boundary Dam Site 4 (courtesy of P.F.R.A.).

(from Geological Implications of Valley Rebound by D. S. Matheson and S. Thomson in Can. J. Earth Sci. 10, 1973, p 961-978)

REPORTED VALLEY REBOUND AT BOUNDARY DAM SITE

J. D. Mollard And Associates Limited

Figure 11

PHOTOLINEAMENT SET AND JOINT SET ORIENTATIONS GIVING DATA SOURCE AND OTHER INFORMATION

1 – GREGGS 1989 REPORT SHOWING FIVE FAULTS TRENDING PRECISELY N45°E AND N45°W IN THE OLDMAN RIVER DAM AREA (FIGURE 1, GREGGS).

2 – MAUGHAN AND PERRY 1986. LINEAMENTS IN THE NORTHERN GREAT PLAINS, UNITED STATES (FIGURE 2, GREGGS).

3 – DOWNEY ET AL. 1987. PREFERRED LINEAMENT AND FAULT ORIENTATIONS IN THE NORTHERN GREAT PLAINS, UNITED STATES (FIGURE 3, GREGGS).

4 – FOUR PROMINENT JOINT SETS MAPPED BY UMA-ACRES GEOLOGISTS DURING DAM AND TUNNEL CONSTRUCTION AT THE OLDMAN RIVER DAM SITE.

5 – OLDMAN RIVER DAM AREA PRELIMINARY JOINT ROSE DIAGRAM PREPARED BY W.K. SAVIGNY ET AL., 1985.

6 – LINEAMENTS IN THE TOPOGRAPHY AND DRAINAGE AT THE OLDMAN RIVER DAM SITE. MAPPED BY MOLLARD IN PINCHER CREEK ON APRIL 17, 1989, AND IN REGINA APRIL 22, 1989. APPROX. AREA: 1 MI^2. NUMBER OF LINEAMENTS: 53.

7 – DOMINANT JOINT STRIKE AND DIP AT 27 STATIONS AS SHOWN ON 1:5000 TOPOGRAPHIC MAP OF THE SITE AREA. PLOTTED BY UMA-ACRES GEOLOGISTS.

8 – PREFERRED PHOTOLINEAMENT ORIENTATIONS, MAPPED FROM 1:80,000 AIRPHOTOS FLOWN JULY 20, 1970. COVERS THE OLDMAN DAM AND RESERVOIR AREA EAST OF THE ROCKY MOUNTAIN FORELAND THRUST BELT. MAPPED BY MOLLARD APRIL 14 AND 20, 1989. APPROX. AREA: 122 MI^2. NUMBER OF PHOTOLINEAMENTS: 320.

9 – CENTRAL PORTION OF A 1:1,000,000 ENHANCED LANDSAT THEMATIC MAPPER IMAGE ACQUIRED AUGUST 7, 1986. MAPPED BY MOLLARD APRIL 18 AND 22, 1989. APPROX. AREA: 7000 MI^2. NUMBER OF PHOTOLINEAMENTS: 227.

10 – REGIONAL PHOTOLINEAMENT TRACE TRENDS IN SOUTHERN SASKATCHEWAN. MOLLARD 1956-1960 AND MOLLARD 1985-87 (N-S AND E-W TRENDS IGNORED). PENNER AND MOLLARD 1987-1989 (INCLUDES N-S AND E-W TRENDS). ROUGHLY ESTIMATED APPROX. AREA: 50,000 MI^2 IN 8 AREAS. ROUGHLY ESTIMATED APPROX. NUMBER OF PHOTOLINEAMENTS: 10,000.

11 – REGIONAL PHOTOLINEAMENT TRACE TRENDS IN SOUTHERN ALBERTA AND WESTERN SASKATCHEWAN. BLANCHET 1957. (NOTE: N-S AND E-W TRENDS IGNORED BY BLANCHET BECAUSE OF THE N-S AND E-W LAND SURVEY AND LAND USE SYSTEM).

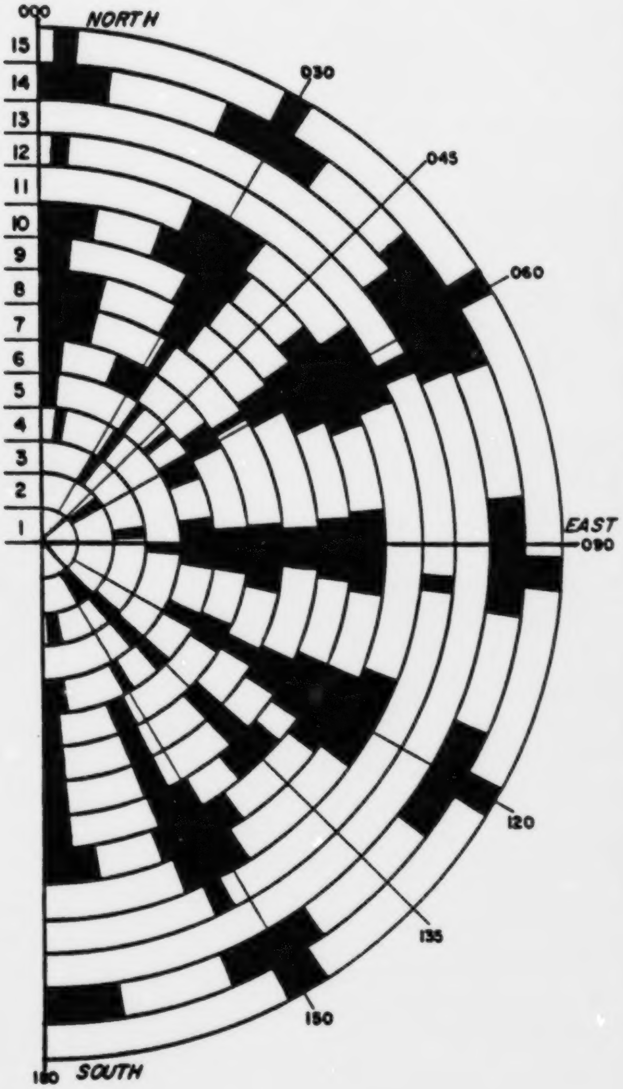
12 – MEAN DOMINANT REGIONAL JOINT SET TRENDS IN THE OLDMAN RIVER DAM AREA REPORTED BY BABCOCK, 1973.

13 – RANGE IN MAXIMUM HORIZONTAL COMPRESSIVE STRESS TRAJECTORY IN THE EARTH'S CRUST (S_{HMAX}). FROM BELL, BABCOCK, GOUGH, ADAMS, COX, KAISER AND OTHERS.

14 – GENERALIZED AZIMUTHAL RANGE OF ORIENTATIONS OF SIX DOMINANT REGIONAL AND LOCAL PHOTOLINEAMENT SETS AND JOINT SETS FROM TRENDS SHOWN IN 1 TO 13. TYPICALLY PEAK TRENDS OCCUR IN THE RANGES N10°W to N10°E, N20-35°E, N50-65°E, N85°-105°E, N20-35°W,N50-65°W.

15 – SIX MEAN ORIENTATIONS OF PERVASIVE GLOBAL ORTHOGONAL FRACTURE SETS, REFERRED TO BY SOME AS THE PERVASIVE REGMATIC FRACTURE PATTERN. A TYPICAL AZIMUTHAL RANGE FOR EACH SET IS 15 TO 20°. FROM V.A. GREGOR (UNPUBLISHED PAPER SUBMITTED TO AAPG IN 1989). DR. GOUGH (AND PERHAPS OTHERS) MIGHT BE INTERESTED IN GREGOR'S PAPER, WHICH WAS REVIEWED BY ME, BOB HODGSON, BOB GREGGS, AND ED KLOVAN, CHIEF GEOLOGIST, HUSKY OIL. MR. GREGOR IS RETIRED AND HIS PRESENTT ADDRESS IS:

MR. V. A. GREGOR, M.ENG., M.SC., P.HG
P O BOX 469
HIXON, BRITISH COLUMBIA
V0K 1S0



GLOBAL, REGIONAL, AND LOCAL PREFERRED PHOTOLINEAMENT SET AND JOINT SET COMPARISON

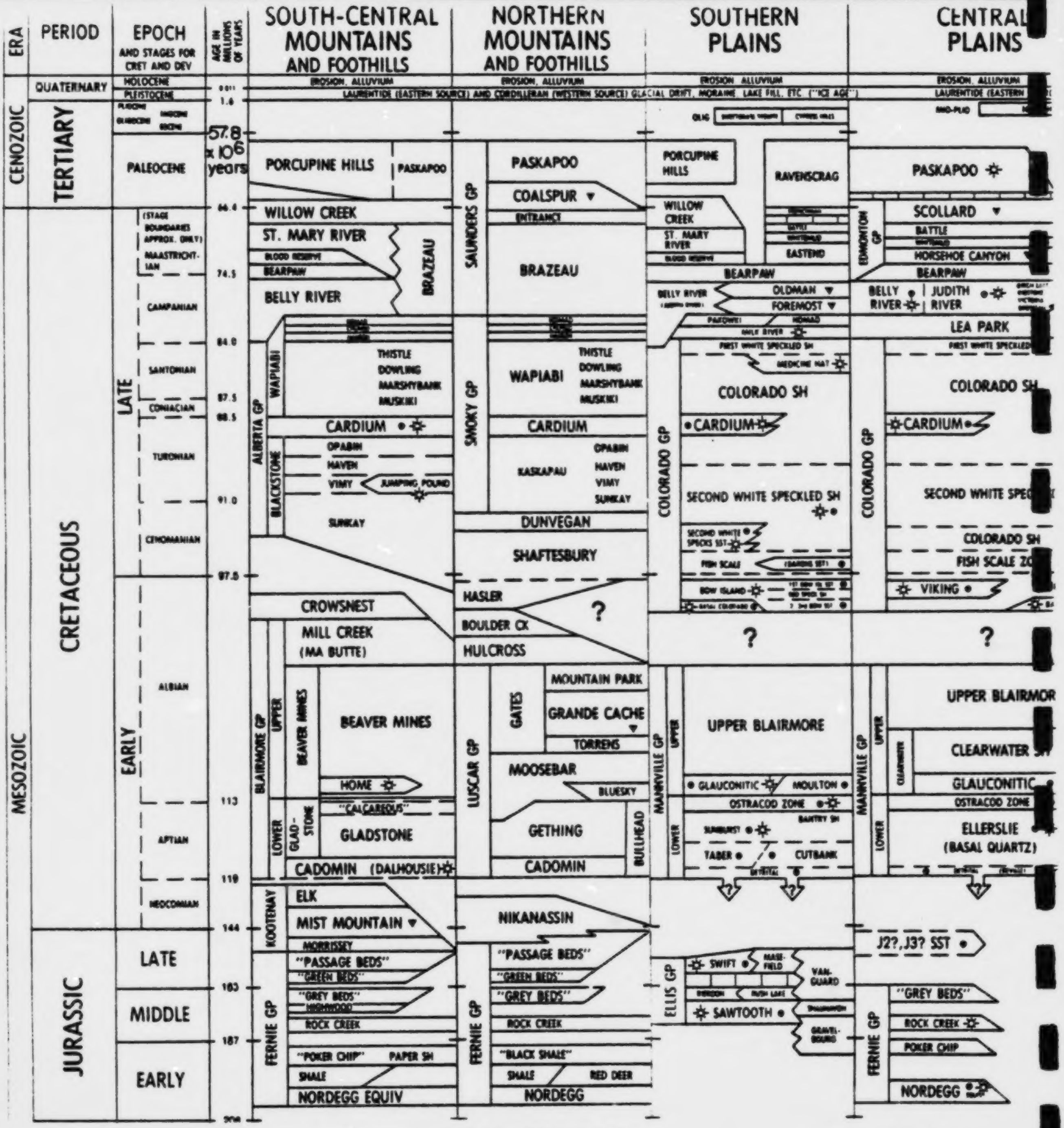
OLDMAN RIVER DAM AND LOWER RESERVOIR STUDY

J.D. Mollard and Associates Limited
April, 1989

FIGURE 12

AGAT Laboratories

TABLE OF FORMATIONS OF ALBERTA


ERA
PERIOD
EPOCH
AND STAGES FOR CRET AND DEV
AGE IN MILLIONS OF YEARS
SOUTH-CENTRAL MOUNTAINS AND FOOTHILLS
NORTHERN MOUNTAINS AND FOOTHILLS
SOUTHERN PLAINS
CENTRAL PLAINS
QUATERNARY
HOLOCENE
PLEISTOCENE
EROSION, ALLUVIUM
LAURENTIDE (EASTERN SOURCE) AND CORDILLERAN (WESTERN SOURCE) GLACIAL DRIFT, MORAINE, LAKE FILL, ETC ("ICE AGE")
CENOZOIC
TERTIARY
PALEOCENE
57.8 x 10^6 years
PORCUPINE HILLS
PASKAPOO
SAUNDERS GP
COALSPUR
RAVENSCRAG
MESOZOIC
CRETACEOUS
LATE
EARLY
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
NEOCOMIAN
WILLOW CREEK
ST. MARY RIVER
BLOOD RESERVE
BEARPAW
BELLY RIVER
BRAZEAU
ENTRANCE
EASTEND
EDMONTON GP
SCOLLARD
BATTLE
HORSESHOE CANYON
OLDMAN
FOREMOST
JUDITH RIVER
PAKOWKI
MILK RIVER
LEA PARK
FIRST WHITE SPECKLED SH
MEDICINE HAT
ALBERTA GP
WAPIABI
THISTLE
DOWLING
MARSHYBANK
MUSKIKI
SMOKY GP
COLORADO SH
COLORADO GP
CARDIUM
BLACKSTONE
OPABIN
HAVEN
VIMY
JUMPING POUND
SUNKAY
KASKAPAU
SECOND WHITE SPECKLED SH
SECOND WHITE SPECKS SST
DUNVEGAN
SHAFTESBURY
FISH SCALE
BOW ISLAND
VIKING
CROWSNEST
HASLER
MILL CREEK (MA BUTTE)
BOULDER CK
HULCROSS
?
BLAIRMORE GP
UPPER
BEAVER MINES
MOUNTAIN PARK
GATES
GRANDE CACHE
TORRENS
LUSCAR GP
MOOSEBAR
BLUESKY
MANNVILLE GP
UPPER BLAIRMORE
CLEARWATER
GLAUCONITIC
MOULTON
OSTRACOD ZONE
HOME
"CALCAREOUS"
LOWER
GLADSTONE
GETHING
BULLHEAD
SUNBURST
BANTRY SH
TABER
CUTBANK
ELLERSLIE (BASAL QUARTZ)
CADOMIN (DALHOUSIE)
CADOMIN
KOOTENAY
ELK
MIST MOUNTAIN
NIKANASSIN
MORRISSEY
JURASSIC
LATE
MIDDLE
EARLY
"PASSAGE BEDS"
"GREEN BEDS"
"GREY BEDS"
HIGHWOOD
ROCK CREEK
"POKER CHIP"
PAPER SH
"BLACK SHALE"
SHALE
RED DEER
NORDEGG EQUIV
NORDEGG
FERNIE GP
ELLIS GP
SWIFT
MASEFIELD
VANGUARD
SAWTOOTH
GRAVELBOURG
J2?, J3? SST
POKER CHIP
0.011
1.6
66.4
74.5
84.0
87.5
88.5
91.0
97.5
113
119
144
163
187
208

1988 EDITION

FIGURE 13

TEL.: (403) 291-2428

APPENDIX A5

Dr. G. Ozoray, P.Geol.

Dr. G. Ozoray obtained his M.Sc. in geology in 1955 at the L. Eotvos University, Budapest, Hungary, and his Ph.D. in applied geology (hydrogeology) in 1965 at the L. Kossuth University, Debrecen, Hungary. Presently he is a hydrogeologist with the Hydrogeology Branch of Alberta Environment. During his career he has been involved in work on many hydrogeological projects on four continents (Asia, Africa, Europe and North America) for the United Nations and other agencies. Among other relevant projects, he was in charge of the reconnaissance hydrogeological mapping of Alberta carried out by the Alberta Research Council. He has published papers on the morphotectonics of Alberta.

Alberta MEMORANDUM

ENVIRONMENT

TECHNICAL SERVICES DIVISION

FROM G. Ozoray, Hydrogeologist
Hydrogeology Branch

OUR FILE REFERENCE 50.2.2.7.9

YOUR FILE REFERENCE

TO J. Thiessen
Project Manager, Oldman River Dam
Alberta Public Works
Supply and Services

DATE April 20, 1989

TELEPHONE 427-6231

SUBJECT REMARKS ON " DR. R. G. GREGGS:
PRELIMINARY EVALUATION OF THE BEDROCK STRUCTURE
- OLDMAN RIVER DAM SITE AREA, SOUTHERN ALBERTA"

In my Memo of April 20, 1989 to you, I have reviewed the above referred report (referred to in this Memo as "the structure report") by Dr. Robert G. Greggs of Greggs & Assoc. Geological Consultants Ltd., prepared for the "Friends of the Oldman River". Since then, on April 17 and 18, I participated in a meeting of various experts, discussing topics connected with the Oldman River Dam with an emphasis on the structure report. More to the point, I had the opportunity to visit the dam site and other locations in the field relevant to Dr. Greggs' proposed structural lines and, also, to see some of the drilling cores mentioned by him.

Based on my field visit and on my viewing the cores, I have formulated my opinion on the structure report and its conclusions and proposals, as follows.

My original evaluation of the structure report, as I expressed it in my Memo of April 12, was fundamentally correct, though now I am in a position of using more firm expressions.

The structure report concludes that there is (or perhaps more precisely: there might be) a serious hazard to the safety of the dam due to structural weakness of the bedrock, and because of drainage by buried channels. I have not found any evidence supporting such a conclusion.

In the structure report the NE-SW/NW-SE and N-S/E-W lineament systems are discussed in detail globally and in North America and a considerable number of references is listed. I do not doubt the existence of those systems, indeed I can even add two of my own papers to the reference list:
-- Tectonic control of morphology on the Canadian Interior Plains; 22nd International Geographical Congress, Monteral, International Geography, Vol. 1, pp. 51-54.
-- Structural control of morphology in Alberta; The Albertan

Geographer, No. 8, pp. 35-42.

The global/western Canadian lineament pattern has some relevance to the geological background of the dam site and it is worth while to spend a paragraph or so on it. However, without a body of local observations it tells us little about conditions at the dam site. It seems that the author of the structure report visited the site only once; it is not clear whether any actual field work has been done.

The point is, that the structure report supposes that a lineament, that is, a discernible line on the surface or a linear arrangement of phenomena, is and must be a tectonic element; this is a serious mistake. Moreover, the structure report implies, at places even explicitly states that those lines must be faults (that is, fractures along which substantial vertical or horizontal relative movement of the rock masses has happened in the geological past). This is also a serious mistake. The structure report further implies that along those faults, whose existence has not been proven yet, the entirely hypothetical mass movement has happened recently.

The dire warning is partly based on a confusion of phenomena. Namely, a lineament does not necessarily imply fractures (discontinuities within the rock mass). Also, there are many kinds of fractures and their consequences for engineering geology are vastly different. The structure report makes no distinction between faults and joints. Along joints, no discernible mass movement has occurred. Along microfaults, small but noticeable movement has occurred. A microfault usually crosses only a few beds and might end at a bedding plane. Faults are caused by major mass movement of a few or many meters; also, many beds or thick non-bedded rock bodies are crossed.

A "Fault locations" sketch showing five conjectural fault lines (Fig. 1) is given in the structure report. The topic is also discussed in some detail in the text. This is the main point of the whole structure report. In the field, however, I have not found any evidence for faulting. On the contrary, at the better exposed sites I have noticed a remarkable continuity of bedding.

Within the area there are many lineaments (more than those mentioned in the structure report). Those lineaments are best interpreted as zones of heavy jointing. Indeed, joints, some confined to a few beds, others crossing many beds, are present at all outcrops and rock exposures. That is to be expected, and is not any way special or unusual at this location, and the phenomenon has been duly recorded previously.

There are signs of horizontal shear and fragmentation in some thin-bedded to laminar mudstone beds. Such fragmentation occurs within the beds due to horizontal stress. Slickensides often develop within such beds and I have seen that phenomenon in several exposed beds. The slickensides noticed in several cores are compatible with horizontal shear and they are not signs of faulting as supposed in the structure report. There is some fracture porosity in the area, and signs of some past minor mass movements: there is a microfault exposed at the construction site; also, there is minimum one small scale intra-formational slump exposed. These have been noted before, being revealed by the test drillings or exposed at the constuction site during excavations.

There are a number of generalities and truisms in the structure report with little or no relevance to the actual site but I do not go into those here. However, the following statement is misleading in the present context: "The older the rock, the more fracturing, due to a longer tectonic history" (p. 23). That unit of the hard rock which outcrops or subcrops in the area (locally, the youngest bedrock unit) is more fractured than the (older) unit underlying it. This is due to the impact of glacial loading, drag and unloading, isostatic adjustment, valley rebound (cliffs of the Oldman River) and weathering. Incidentally, these are the processes that have in part caused the well observable joints of the outcrops and of the valley bottom and not faulting.

In the structure report are mentioned " ... reports of recent landslides along scarps" (p. 15), but unfortunately, without giving any concrete details. However, the "Preliminary report on the geology of the Oldman River Dam reservoir area" by Dr. J. D. Mollard deals with slides in more detail. The design engineers are clearly aware of the phenomenon. As they should be: slumps along erosion-exposed bedrock slopes, especially in the talus under the exposures, are common everywhere in the Interior Plains. Naturally, all new slumps have to be noted and (if the dam or the reservoir might be affected) be taken into consideration.

It is also remarked in the structure report that "Tectonic deformation features indicate not only planes of weakness, but frequently zones of high permeability" (p. 11). That is often so; from references in the structure report I understand that grouting is planned to rectify the situation. I would add, however, that the often referred to slickensides may also be barriers to groundwater movement, the smeared clayey material acting as waterproofing in faults. (Which, on the other hand, may complicate the engineering geological situation with the possible consequences of inadequate drainage.)

The question of buried valleys is also raised in the structure report (p. 16) with the suggestion that lineament A might coincide with a buried valley segment. That, if so, may somewnat modify the way basic flow in the river is maintained. The buried valley problem is discussed in more detail in Dr. Mollard's preliminary geological report so I refer to that source.

Concluding, my opinion is that the structure report moves too much in generalities and contributes little if any new information to the geology of the dam and reservoir sites. The area shows no more widespread or more dangerous signs of lineament presence, jointing, microfaults, fracture porosity, slumping and buried valley phenomenon as any comparable sized piece of land in the general geographic zone. The area is advantageous in that there are no signs of the presence of major faults. The studies already executed, including core drilling, seem to be adequate to pinpoint the problems. The engineering design must take into consideration the existing problems and the geological characteristics of the area. It lies outside of my qualifications to attempt to decide whether this has already been adequately done.

Dr. Gyorgy Ozoray
Professional Geologist
Hydrogeologist

APPENDIX A6

Dr. K.W. Savigny, P.Eng., P.Geol.

Dr. K.W. Savigny was the senior engineering geologist in charge of the investigations of the Oldman River Dam and Spillway foundations. He prepared the Foundation Exploration and Buried Valley Investigation appendices of the Oldman River Dam Preliminary Engineering Report. Dr. Savigny obtained his B.Sc. in Geological Engineering from Queen's University in 1971 and his Ph.D. in Civil-Geotechnical Engineering from the University of Alberta in 1980. He is now an Associate Professor in the Geological Engineering program, Department of Geological Sciences at the University of British Columbia. His consulting experience has included site investigations for, and design of, dam projects, pipelines, soil and rock mass movements and slope stability, road and railway tunnels and heavy industrial projects.

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May 8, 1989

File: 17-550-36

UMA Engineering Ltd.
17007 - 107 Avenue
EDMONTON, Alberta
T5S 1G3

Attention: Mr. D.B. Chalcroft, P.Eng.
Project Manager

RE: OLDMAN RIVER DAM
REVIEW OF GREGGS' REPORT

Dear Sir:

We have reviewed the report entitled "Preliminary Evaluation of the Bedrock Structure - Oldman River Dam Site Area, Southern Alberta", dated February, 1989, by Dr. Robert G. Greggs, P.Geol. of Greggs & Associates Geological Consultants Ltd. As part of this review, Dr. Wayne Savigny, P.Eng., P.Geol. attended a two-day meeting of project engineers, geologists and geophysicists at Pincher Creek on April 17 and 18, 1989, which included field visits to the Oldman River Dam and surrounding area.

On the basis of our review, we disagree with many of the conclusions, and have serious concerns as to the adequacy of evidence cited in support of the conclusions presented in the Greggs report. Our specific comments follow. For convenience, we have adopted the same organizational structure as the Greggs report. A list of references is given in Appendix A, attached.

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METHODOLOGY CRITIQUE

Dr. Greggs (p.5, para.2) references Russell and Landes (1940) as saying "....vertical faulting is thoroughly documented in this general area....". It should be pointed out that Russell and Landes (1940) deal almost exclusively with the area east of approximately Lethbridge (113° longitude). They consider about 15 different regional structures of which only two are believed to be associated with faults.

The first and closest fault to the dam site is at the City of Lethbridge where the following description is given: "Folds are broken only by normal faults, most.... small magnitude and doubtless extending to no great depth....Only two are of sufficient magnitude to carry to depth." The second area of faulting is south of Medicine Hat where uncertainty is expressed as to whether off-set beds are a result of slope instability or faulting. Therefore, Dr. Greggs' reference does not appear consistent with statements by Russell and Landes (1940). Moreover, several more recent and widely referenced publications, which Dr. Greggs does not cite, show no ground surface faulting east of the Disturbed Belt in the Pincher Creek - Fort McLeod area (Douglas, 1950; Irish, 1967; Price, 1966; Gordy, et al., 1977).

GEOLOGICAL BACKGROUND CRITIQUE

Orthogonal Fracture Pattern

The Greggs report (p.7, para.1) refers to "....the regmatic, or orthogonal fracture system....". Although it only alludes to the origin of this system, some understanding is important as it influences the characteristics of associated faulting. There are generally two ways of considering how this system originated: A tectonic origin, which is widely documented in the literature; and, a variety of alternative origins, none of which appears to be generally accepted in the literature as a causative factor. These possible origins are discussed below:

Tectonic:

The Oldman River Dam site is situated in foothills near the front of the Rocky Mountains. Compressive stresses which gave rise to the nearby Rocky Mountains caused fractures and folds in both the mountains and foothills. The key difference between these two regions is that the magnitude of stresses decreased in an eastward direction from the mountains to the foothills. Large-scale brittle failure of rocks, which we interpret as faulting, is believed to be limited to the mountains where stresses were higher. Moreover, these faults dip westward at angles varying from 30° to 60°.

To our knowledge, no faults are known to break the surface in the dam site area. Folds and associated fractures are found in the Oldman River Dam area. Fracture patterns form an orthogonal system and are generally subvertical as documented in our 1985 report.

During the recent field trip to Pincher Creek, Dr. Savigny inspected several outcrops at locations where faults are shown in the Greggs report. No evidence of faulting was recognized in rocks exposed at these locations, however most outcrops were discontinuous, and some were in an advanced state of raveling. To confirm that faults are not present would require extensive drilling and seismic studies. In our opinion, the geological information available to us provides little justification for such work when the following factors are considered:

1) A lack of geomorphic features such as prominent lineament trends, anomalous weathering and fracture patterns, and groundwater discharge associated with 'tectonically active' faults.

2) No reported macroscopic vertical faulting in the area in published references by the Geological Survey of Canada and the Canadian Society of Petroleum Geologists.

3) No observed evidence of macroscopic vertical faulting in detailed studies completed as part of our 1985 site investigation studies.

Alternatives:

There is little doubt that the Western Canada Sedimentary Basin is affected by widely separated subvertical faults which have similar trends to the orthogonal fracture system described above. Two of the alternative theories for their origin appear to be technically sound.

First, Mollard (1988) reports lineament trends and associated faulting which are a response to dissolution of evaporite formations at depth. To our knowledge, no evaporite formations are found as far west in the Western Canada Sedimentary Basin as the Oldman Dam site. These rock units are removed from the section by an unconformity west of approximately Drumheller (Ziegler, 1969).

Second, Scheidegger (1983), Jones (1980) and Walcott (1970) consider the widely separated subvertical faults are an indication of brittle deformation of the lithosphere-asthenosphere interaction as part of isostatic adjustments. Again, to our knowledge, there is no report of these subvertical faults in the Oldman River Dam area.

Other Comments:

The Greggs report (p.7, para.1) describes fractures in the Western Canada Sedimentary basin as "....arranged in a systematic and persistent pattern, vertically disposed and subequally spaced". This description is consistent with our observations as reported in the 1985 foundation exploration report. We disagree with Dr. Greggs' follow-up statements: first (p.7, para.2), "This regmatic fracture pattern results in vertical bounding faults...."; and, second (p.15, para.1), "The orthogonal fracture pattern is characterized by regular spacing of master faults and minor faults".

Fracture patterns are traditionally viewed as distinctive and without association with fault patterns. The deduction that fracture patterns are also fault patterns does not appear justified unless supported by other evidence. Dr. Greggs' evidence, which is only given by implication (p.15, para.2), includes "The degree of fracturing, indications from seismic interpretations, geomorphic features and reports of recent landslides along scarps....". Our work indicates the degree of fracturing is random throughout the site, and the presence of fractures controls geomorphic development (including landslides). Notwithstanding support of Dr. Greggs' seismic evidence by others, we conclude that the Greggs report provides insufficient evidence to support either the presence of vertical faults or any association between vertical fractures and faults.

The Greggs report states "....faults....produce a mosaic of horsts and grabens, which exhibit reversals of vertical movement throughout geological time...." (p.7, para.2). The difference between geological time and life-of-structure time needs to be considered in evaluating the significance of this statement. Engineers deal in life-of-structure time, not geological time. For example, Jones (1980) reports 18 to 23 metres of movement of marker beds across vertical faults at other locations in the Alberta Plains. The marker beds are Lower Cretaceous age, 136 to 100 million years ago. This means the most conservative estimate of the average rate of movement is 0.0002 mm/year. The Rocky Mountains evolved since the Lower Cretaceous Period and faults in the mountain belt show many tens of kilometres of movement. Even if movements are intermittent with significant variations in the average rate, movements in the plains/foothills area will be several orders of magnitude smaller than in the mountains; yet many major projects have been built and successfully operated in the mountains as well as the plains/foothills area. We conclude that the connotation of time in the Greggs statement does not appear significant within the design life of the Oldman Dam structure.

Geomorphology

The Greggs report (p.7, para.3) states "Modern drainage patterns strongly reflect the underlying basement structure...". We do not agree with this conclusion. A basement structure infers one in Precambrian age crystalline rocks which lie at considerable depth below the geoclinal wedge of sedimentary rocks. Modern drainage is much more likely to reflect structures of rocks into which surface drainage is incised; the youngest rocks in the geoclinal wedge in this location.

Stress Patterns

The nature of fractures in the test shaft (logged by Dr. Savigny) indicate the minimum principal stress is horizontal in the abutments and vertical in the foundation areas of the proposed dam structure. The high angle of the mesoscopic fault in the flip bucket excavation is further evidence that the minimum principal stress is horizontal in the abutments. These stress orientations would be expected in view of the fact that many hundreds of metres of sediment have been removed from the site since diagenesis, and that locked-in stresses are relieved by isostatic rebound and by lateral displacement associated with valley erosion.

TECTONIC DEFORMATION CRITIQUE

Tectonic fabric is described by Dr. Greggs (p.10, para.1) as including "....fractures, slickensides, faults, brecciation, ...fault gouge, and stylolites....intervals of poor core recovery....addition of hydrothermal minerals along fracture planes....strain cavities, and exaggerated dip angles....on bedding planes". Many of these features can also develop in response to deformations during consolidation, glaciotectonic deformations and lateral stress release during valley down-cutting. Hence, it would be incorrect to conclude that such features alone are evidence of tectonic deformation.

The Greggs report (p.11, para.5) states "Induced fractures have a very specific morphology and will occur uniformly throughout the core". Induced fractures generally have a specific morphology, but their distribution is related to drilling procedures and personnel as well as stratigraphy. Therefore, we do not agree with Dr. Greggs statements.

FAULT LOCATIONS CRITIQUE

The Greggs report (p.5, para.2) states "The structural setting of the Oldman River dam area was integrated into the North American stress and fault patterns by correlating topographic maps with previously published data....". However, on page 8, paragraph 1, the Greggs report stresses the need for "....photolineation studies...." in locating tectonic landforms. The question arises as to how the faults in Figure 1 of the Greggs report are defined? It appears as though the normal minimum location procedure utilizing airphoto and/or satellite imagery has not been adhered to. Nor does there appear to have been any definition of a fault plane from field studies or from correlation of oil well or seismic data from the area. If these assumptions are correct, Figure 1 of the Greggs report should be considered as preliminary or speculative.

The Greggs report (p.16, para.2) states "....the floor of the valley is more densely jointed than the walls....this indicates that the river is incised into a weak zone (ie. fault trace)...". We do not agree with this conclusion. The location of the Oldman River valley in the immediate reach of the dam site is a result of deepening of a channel originally opened by glacial meltwater. Erosion of the valley, once Quaternary subcrop was passed, was controlled by orthogonal joint patterns. The fact that stratigraphic marker beds can be correlated across the valley with no bedding attitude anomalies precludes the presence of a macroscopic fault.

Some increase in the frequency of fractures is common in the bottom of deep valleys in this physiographic region. This is attributed to stresses and deformations associated with opening of the valley. The mesoscopic thrust fault found in the right abutment core trench is another stress deformation response to this process.

IMPLICATIONS FOR SITE STABILITY CRITIQUE

The Greggs report (p.19, para.2) states "...there is conclusive evidence for pervasive vertical faulting in the Oldman River Dam Project area". As discussed above, we believe that the arguments for vertical faulting which have been put forward are tenuous, and that the evidence which has been quoted probably relates to other mechanisms. Thus, we do not believe that vertical faulting is associated with the fracture systems of the area. Moreover, we see no justification as to why vertical faults should be expected in association with fracture systems.

Where Dr. Greggs refers to "greasing" and "jiggling" (p.20, para.2), we assume he refers to induced seismicity. This is a well known condition that was addressed by others on the UMA team.

The Greggs report (p.20, para.3) infers that the area is tectonically active. 'Tectonically active' means the presence of faults showing evidence of a single movement within the last 100,000 years, or repeated movements within the last 500,000 years. We are aware of no evidence that indicates the site is tectonically active within these generally accepted guidelines.

RECOMMENDATIONS CRITIQUE

We believe all necessary geological investigation work was done by the UMA team during the 1985 investigations for the design requirements at that time. We understand that further geological work has been done as part of design and construction. On the basis of the recent meetings in Pincher Creek and tour of the construction work, we are pleased that the original geological model for the site continues to appear to be an accurate representation of geological conditions. We see no justification for further studies as recommended in the Greggs report.

CONCLUSIONS CRITIQUE

The Greggs report (p.23, para.1) states "The degree of fracturing described from the cores is as severe, if not more so, than fractured oil reservoirs which produce hydrocarbons from depths of 1000 m. (The older the rock, the more fracturing, due to a longer tectonic history)". This statement ignores the influence of weathering and other terrestrial geomorphic processes such as freeze-thaw cycling, glaciation, etc. These processes cause physical and chemical breakdown of near-surface rocks, but have negligible influence on deeply buried rocks. The distribution of residual soils in warmer climates is clear evidence that the limiting effect of this process is the breakdown of near-surface rocks to soil.

The statements in paragraph 2, page 23 infer that the failure of Teton Dam was related to faulting. The summary report of the Independent Panel to Review the Cause of Teton Dam Failure makes no mention of faulting as a contributing cause of failure.

CLOSURE

If you have any questions or comments about the foregoing review, please contact us.

Yours very truly,
Thurber Consultants Ltd.

May 11 89

J.M. Laing, P.Eng.,
Review Principal

K. Wayne Savigny, P.Eng., P.Geol.,
Project Engineer/Geologist

KWS/bdl

attachments

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Date May 11, 1989.
PERMIT NUMBER: P 355
The Association of Professional Engineers, Geologists and Geophysicists of Alberta

APPENDIX A

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APPENDIX A7

Dr. L. Wolofsky

Dr. L. Wolofsky prepared the seismicity study for the Oldman River Dam Project in collaboration with Dr. D.I. Gough. Dr. Wolofsky has earned four university degrees including a Ph.D. from McGill University in 1957. He is currently an independent consultant geologist to international banks, government agencies, power utilities and other organizations in many countries. During his career Dr. Wolofsky has provided engineering geology input to more than 40 dam projects, many of them located in seismically active areas such as the Himalayas, Iran, Turkey, Yugoslavia and the Central and South American Cordilleras.

L. WOLOFSKY, Ph. D. Consulting Geologist

25 April 1989

Mr. D.B. Chalcroft, P.Eng.
Project Manager
UMA Engineering Limited
17007 - 107 Avenue
Edmonton, Alberta
L2E 6N8

SUBJECT: Oldman River Project. Report of Dr. Robert Greggs to F.O.M.

Dear Sir,

This is in response to your letter of 21 April 1989, your reference 2496-031-00-1008-1.30. I have read Dr. Robert G. Greggs' report "Preliminary evaluation of the bedrock structure — Oldman River dam site area, Southern Alberta" prepared for the President of Friends of the Oldman River and dated February 1989. I have also visited the site and vicinity, examined some of the outcrops, drill cores and documents, and discussed the geological conditions as displayed in drill cores, permeability tests, grouting results, tunnels, outcrops, and excavations with site staff and with other consultants.

Because my primary task in this project is to provide the designers with information with respect to seismic conditions, I paid special attention to faults which might generate relevant earthquakes. So far as I have been able to determine, there are no such faults in the vicinity of the site. I have been unable to confirm a factual basis for Dr. Greggs' apparent concern for the safety of the dam.

General
Although the logic sequence is not clearly described, Dr. Greggs' views appear to require the following chain of five assertions and assumptions:

1. There are at least 5 major linear topographic features in the project area.
2. Each one marks the intersection of a bedrock fracture with the ground surface.
3. Each of these fractures is a vertical fault.
4. These faults are still active and may move in future, causing "jiggling".
5. Such movements may endanger the structures and the integrity of the reservoir.

In my opinion, these assertions and assumptions are not supported by convincing evidence in his report and are contradicted by other evidence. It is also relevant to

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note that, if they were valid, they would apply not only to the Oldman River dam but also to many of the existing dams in a large proportion of this continent, including those (especially the Gardner and Nipawin Dams in Saskatchewan) in the areas described by J.D. Mollard in the first R.M. Hardy Memorial Lecture (Canadian Geotechnical Journal, vol. 25, no. 4, pp 749-767, November 1988).

Specific comments

The following comments relate to points raised by Dr. Greggs. The page numbers refer to his report.

1. Features in drill cores (page 5).

I have seen only some of the cores, but these include many of the ones mentioned by Dr. Greggs. The phenomena noted from core logs in Table 1 (pp 13-14) would be expected in near-surface sedimentary rocks of similar types near almost any valley in the Alberta Plain. They are not unusual in dam foundations in general, and it is quite usual to treat them to ensure acceptably low permeability, as is being done at the Oldman site. Indications of shearing are not surprising in view of the rebound history. In the drill cores and rock exposures the shearing appears to be associated with bedding planes, indicating slippage between beds during rebound or other slight warping.

With respect to the distinction between natural fractures and drill-induced fractures in diamond drill cores mentioned by Dr. Greggs (pp 11-12), engineering geologists are well aware of the differences and are accustomed to making this distinction especially when logging RQD values. My experience—in contrast to Dr. Greggs'—has been that core fracturing caused by drill equipment and operation is not uniformly distributed but varies with the type and age of equipment, skill and experience of drillers, vibration of the drill setup, etc.

2. The five lineaments/"faults" (pp 15-18)

On p.19 Dr. Greggs says "there is conclusive evidence for pervasive vertical faulting in the Oldman River Dam Project area" and that he has arrived at this conclusion on the basis of:

—the data provided on the previous pages,

—confirmatory field work, and

—extensive experience with regional basement tectonics.

The data provided are unconvincing. In my opinion, the assertions and assumptions listed on the previous page are not well supported by the material in this report. The field work of the geologists and engineers who have worked on this project full time for months or years, as well as my own observations, do not confirm the presence of these faults, or even of the five lineaments. My own experience with basement tectonics was obtained in other regions (where the basement is exposed), so I will not comment on this point. However, it may be relevant to mention that I have seen faults which are capable of generating appreciable earthquakes in the vicinity of proposed dam projects in several other countries (Peru, Colombia, Nepal) and did not see anything similar in the vicinity of the Oldman River Project.

In most parts of the world, including most of Canada, many lineaments can be detected on satellite images, aerial photos, or even topographic maps. The vast majority are associated with glacial striations, rock stratification, schistosity, foliation, geologic contacts, joints, etc, and very few with active faults. These few are usually distinguished by recognisable features, since their last movements have left traces of scarps, disturbance of Quaternary stratification, offset of streams, etc. Active faults also give rise to earthquakes or microearthquakes, and can be identified by the patterns of earthquakes and microseisms detected.

None of these indications is present in the vicinity of the Oldman River Project. There are no earthquake epicentres in the vicinity of the project, according to the comprehensive data base maintained by the Geological Survey of Canada. Microseismic monitoring by Alberta Environment during the past 2½ years confirms that the area is seismically extremely quiet. Extensive natural and artificial exposures of bedrock along some of Dr. Greggs' lineaments appear normal and do not show offsets of stratification or other features suggestive of faulting. Geologic mapping in the diversion and drainage tunnels excavated at the dam site confirms these observations. If there were old vertical faults which had caused more than a few metres of vertical offset of strata, their presence would be indicated by abrupt variations in the elevations of marker horizons between drill holes. No such variations have been noted.

On the other hand, the rock in the region, in common with most sedimentary rock everywhere, contains joints, some of which are parallel to the directions NE-SW and NW-SE identified by Dr. Greggs as the orientations of his "faults". Lineaments with these orientations, as well as roughly N-S and E-W, are to be expected because of the presence of joints.

The evidence adduced for some of these five supposed faults includes inferences from seismic refraction surveys and drill cores. For seismic refraction (as distinct from reflection) to suggest the presence of a vertical fault, the fault would have to be characterised by an exceptionally wide low-velocity zone, or to have markedly displaced the bedrock surface. Dr. Greggs does not suggest that either of these phenomena can be read from the seismic refraction surveys. He does not state in what manner the survey results support his contentions. With respect to the supposed evidence from drill cores, see 1, above.

Faults resulting from movements in the distant past, which are no longer continuing, are relevant only if they are represented by weak or permeable zones requiring treatment during construction. In view of the practical limit of numbers of exploratory drill holes which can be used to investigate any dam area and the fact that most of the holes were vertical, there can never be a guarantee that all vertical geological structures have been fully explored. The core trench excavation and the grouting program are adequate to locate and treat any such features.

Dr. Greggs refers to a publication by Maugham and Perry (1986) (Dr. Greggs' reference), from which his Fig 2 is derived. He identifies his "fault A" with the lineament (not fault) labelled 'Bridger' on that figure. He says this lineament represents a fault which he extrapolates from the State of Colorado (about 1,100 km southeast from the Oldman River site), although the Bridger lineament is shown in Fig 2 only as far north as the southern part of the State of Montana. For the remainder of the distance to the Alberta border, he relies on his Fig 3, from a paper by Downey et al (1987). On close examination it is evident that nothing in Fig 3 corresponds to the Bridger lineament of Fig 2. In fact, in areas where the two maps overlap, there appears to be little coincidence between either the locations or the bearings of lineaments in the two drawings.

Dr. Greggs notes that the floor of the valley is said to be more densely jointed than the walls. This is a common condition which may be due to any of several causes. If this condition exists in the present case, it is probably because of arching during rebound consequent on erosion and deglaciation. In other words, the location of the valley determined the location of the jointing, not the reverse. In fact, the frequency of joints in the drill cores suggests that there is no great difference between the abutments and the valley bottom in this respect. See the attached figure "Elevation vs. joint frequency in drill holes", but note that most of the joints detected by these (primarily vertical) holes are near-horizontal, and vertical joints are not well represented.

3. Future movement in response to regional stress (p. 19).

If these five faults did exist, they would have to be vertical (as Dr. Greggs assumes they are) in order to produce the straight intersections with the ground surface indicated by the lines he has drawn on the map. They would be oriented parallel to and normal to the regional maximum horizontal stress, which is approximately NE-SW according to Dr. Greggs and others. Therefore the regional stress produces zero shear stress on the faults of both sets, which therefore experience no tendency to move. This is confirmed by the observations of the seismic record and the microseismic monitoring, mentioned above.

Unloading because of erosion and deglaciation can result in slow horizontal and vertical movement in most parts of Canada and other northern countries. Where the rate of movement varies from place to place, differential shear movements may occur across the weakest rock planes (old faults, bedding planes, joints). These kinds of movements result in extremely small relative displacements, and I know of no case where they have caused problems for fill dams.

4. Grouting of the dam foundation (pp 4, 20)

Dr. Greggs contends that "current efforts to seal these bedrock fractures under the dam itself are unlikely to be successful, as the fractures are very deep-seated and grout is also susceptible to fracture, due to the prevailing stress system."

The joints in the foundation rock are not likely to be deep-seated. From data provided by the site, I have plotted the frequency of jointing in drill cores at various elevations, as shown in the attached figure. It is evident that there are few joints at depth. (However, note that vertical joints are not well represented by these drill holes, most of which are vertical, and that complications are introduced by the varying physical properties of strata at different elevations.)

I have examined some of the testing and grouting results to date. The average permeability of the dam foundation rock was originally rather low, and it appears that it is being reduced to negligible levels. There will of course be some normal residual seepage which will contribute to downstream releases, as at almost every dam.

In insoluble rock, such as the rock at the Oldman River site, a grout curtain consists of a volume of rock in which fractures are filled with "veins" of grout in thicknesses from a film to a few millimetres. In most cases these "veins" are probably cracked by blasting vibrations and settlement in the foundation during construction. It is not necessary to call upon "the prevailing stress system" to fracture the grout films. No grout curtain is expected to be perfectly impervious in order to perform its function. The foundations of most dams, including this one, are provided with drainage facilities partly for this reason.

5. "Jiggling" and risk to public safety (pp 4, 20).

It is impossible to be sure what is meant by the word "jiggling". These postulated movements are said to be "intermittent", but not associated with "earthquakes, as commonly understood". In any case, I see no reason to expect movements other than the extremely small and slow ones resulting from normal deformation of the foundation due to isostatic rebound and reloading, which are tolerated by existing structures all over the deglaciated parts of the world.

Dr. Greggs suggests (p.20) that "the amount of water which will be present in the Oldman River reservoir may well act to grease these faults...which would adversely affect the geological stability of the site." It is generally agreed that the pore pressure induced by a reservoir (not the amount of water), and the effective normal stress (not the coefficient of friction) are relevant factors in triggering fault movements related to reservoirs, in the few cases where such movements have occurred. Another necessary condition is a stress/strength relation in the fault which is on the verge of failure before reservoir filling. This is not the situation here. The stresses are moderate and are so oriented, as mentioned above, that they do not subject the NW-SE and NE-SW joints to shear stresses.

6. The failure of Teton Dam (p.23).

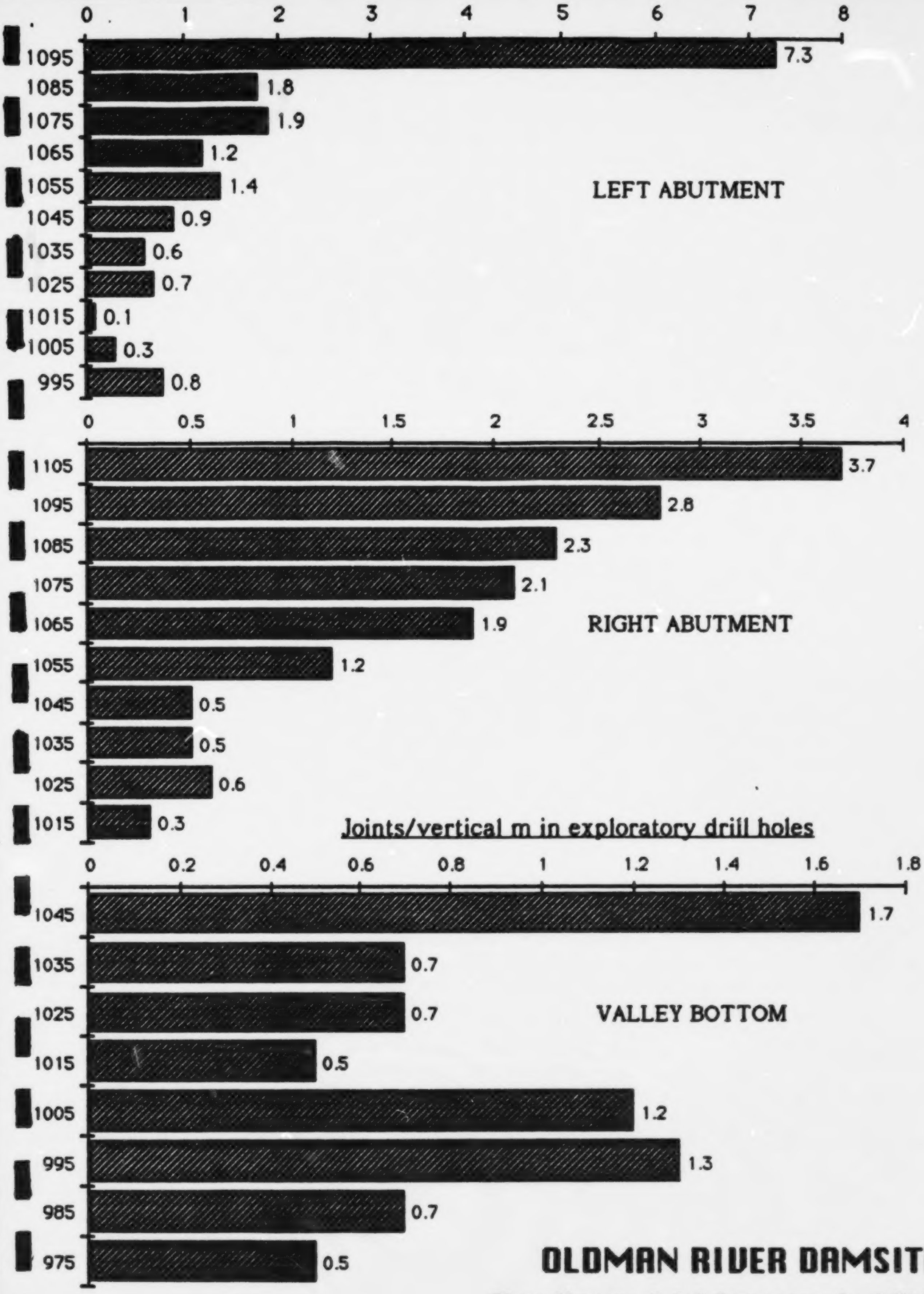
Dr. Greggs introduces this subject in association with a sentence about faulting, implying that the two are related. I can see no relevance of this case to the Oldman River situation.

Dr. Greggs' reference for his source of information about Teton is to an article in the magazine 'Audubon'. Because dam failures are so rare, each one is intensely studied in order to learn as much as possible, and the Teton failure is probably better documented than any other. The book "Dam Failures" edited by Prof G.A. Leonards (Elsevier, 1987) presents all rational points of view on the causes of this failure and references to the voluminous definitive studies.

Yours sincerely,

L. Wolofsky

L. Wolofsky
encl. 1 figure.



LEFT ABUTMENT

RIGHT ABUTMENT

VALLEY BOTTOM

OLDMAN RIVER DAMSITE

Elevation vs. joint frequency in drill holes

APPENDIX B

Report on
"Site Observations. Search for Evidence for Faults Hypothesized by Dr. Greggs."

by

Thurber Consultants Ltd.

APPENDIX B1	Photographs
APPENDIX B2	Follow-up Visit to Geological Site 1.

OLDMAN RIVER DAM
SITE OBSERVATIONS
SEARCH FOR EVIDENCE OF FAULTS
HYPOTHESIZED BY DR. GREGGS

Report Submitted

to

UMA ENGINEERING LTD.

J. M. LAING
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May 16/89

Thurber Consultants Ltd.
Edmonton, Alberta

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Review Principal

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Date May 16, 1989
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The Association of Professional Engineers, Geologists and Geophysicists of Alberta

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May 16/89

May 16, 1989
File: 17-550-37

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05/17/550-37AA

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1. INTRODUCTION

This report describes the geological and geomorphological features observed at 15 sites along the alignments of possible faults postulated in the Greggs and Associates report dated February, 1989. The work was carried out under the supervision of Mr. H. Hartmaier, P.Eng., of UMA/Acres and consisted of a brief reconnaissance and photograph of each site. The more instructive sites were then visited by the project geologists on April 17, 1989.

In his report, Dr. Greggs postulates five vertical faults cross-cutting the dam and reservoir area. The purpose of this study was to inspect rock exposures along the hypothesized fault traces in order to search for surficial evidence of the type of regional faulting Dr. Greggs describes in his report. The type of evidence sought included vertical offsetting of beds or near vertical shear zones, possibly containing fault gouge and/or slickensides.

A total of 15 sites along the fault traces were chosen from maps and air photographs where rock exposure could be expected. Figure B1 shows the location of these sites as well as the approximate location of the 5 faults hypothesized by Dr. Greggs. The field work was conducted on April 14, 15, 16 and 19, 1989 and consisted of a brief site inspection and photograph of each site. It should be noted that detailed geological mapping was beyond the scope of this study.

The rock types encountered were sandstones, siltstones and claystones. The exposed sandstones are generally weathered, locally flaggy, contain sub-horizontal bedding planes and open sub-vertical joints and because of their resistance to weathering often form prominent bluffs. The exposed siltstones range from clayey to sandy, often contain sub-vertical joints and have bedding thicknesses ranging from 10 to 200 cm. The exposed claystones are usually nuggetted (due to weathering), often contain multidirectional internal slickensides, and have bedding thicknesses ranging from 5 to 100 cm.

It should be noted that all of the rock exposures observed (except at Site #9) were weathered and that most of the exposures were located within river valleys. Therefore most of the bedrock observed has undergone such processes as weathering, stress relief and valley rebound. These processes have acted on existing joints as well as other planes of discontinuity such as bedding planes. One would expect that fresh rock would have a much tighter appearance and indeed this was observed in the recent rock excavations at the Oldman River Dam site.

The following pages describe the geological conditions observed at each of the 15 sites. Table B1, at the end of this text, summarizes the geological features which were observed at each of the sites during the field program. The extent and continuity of the rock exposures as well as the jointing characteristics and the type of fault evidence sought are all tabulated.

2. SITE DESCRIPTIONS

Site 1

Site 1 is located northeast of Cowley and just downstream from where Secondary Road 510 crosses the Oldman River. It is at this location where Dr. Greggs postulates Fault C on the basis of his outcrop observations along the Oldman River and in his report includes a photograph of this locality. Unfortunately, the available reproduction of his photograph at the time of the field work was of poor quality and therefore it was difficult to locate the exact portion of the outcrop Dr. Greggs was referring to.

This stretch of the Oldman River in the vicinity of Site 1 contains numerous rock outcrops. Photographs 17-550-37-1, 17-550-37-2, and 17-550-37-3 show three such rock exposures located about 0.6, 1.1 and 1.8 km downstream of the Secondary Road 510 bridge, respectively. These outcrops consist of near vertical bluffs of channel facies sandstones, which are weathered and contain sub-vertical joints with typical apertures of 0 to 5 cm. One enlarged joint system was observed which involved a wedge of rock being displaced about 30 cm. The two upstream exposures of sandstone bluffs are underlain by sub-horizontal mudrock units (siltstone and/or claystone units) which are less resistant than the sandstone and thus form sloping topography which is partially covered by a thin veneer of colluvium (see Photograph 17-550-37-4). The claystones are weathered, nuggetted and often contain internal slickensides.

Dr. Greggs shows his hypothesized Fault C intersecting the Oldman River approximately 0.7 km downstream from the Secondary Road 510 bridge. A brief examination of the rock exposures in this vicinity, including both upstream and downstream, as well as a walk up the two coulees entering the north side of the river (see Photograph 17-550-37-5), revealed no visible offset of beds. Some sub-horizontal beds could be traced for about 100 m across large rock exposures. No substantial offset nor any severe sub-vertical fracturing which may constitute a shear zone were observed.

Photograph 17-550-37-6 is a view looking northeast at a sandstone exposure along the Oldman River, about 0.6 km downstream of the Secondary Road 510 bridge. This may be the same location as Plate B in the Greggs and Associates Report, where Dr. Greggs describes an enlarged joint system in sandstone and postulates a fault location.

Site 2

Site 2 is located along a northwest-southeast trending ridge of rock outcrop which extends from about 6 to 8 km northwest of the dam site and immediately west of Tennessee Creek. Dr. Greggs' hypothesized Fault B appears to parallel this ridge. The ridge consists of a few hundred metres of sandstone exposure which is weathered, locally flaggy and contains sub-horizontal bedding planes and sub-vertical joints open as much as 10 cm. Photographs 17-550-37-7 and 17-550-37-8 are views looking northwest along the trace of Dr. Greggs' Fault B. No bedding offset, slickensides or gouge was observed.

Site 3

Site 3 is located along Tennessee Creek, immediately south of Secondary Road 510. Photograph 17-550-37-9 is a view of the site looking south. No rock outcrop was evident at this site.

Site 4

Site 4 is located about 2 km north of Bitango Bridge where Dr. Greggs' hypothesized Fault A and Fault X intersect. Photograph 17-550-37-10 shows some rock exposure on the D.G. Lewis property close to this intersection. The exposure is about 50 m long and consists of weathered sandstone which is locally flaggy and contains open sub-vertical joints, many of which are truncated by sub-horizontal bedding planes.

Site 5

Site 5 is located along the Oldman River about 0.8 km upstream from Bitango Bridge where Dr. Greggs' hypothesized Fault B and Fault X intersect. The site contains bedrock exposure along the north bank of the Oldman River and up the coulee immediately east of the mouth of Tennessee Creek. Photographs 17-550-37-11 and 17-550-37-12 show the exposure along the north bank of the Oldman River while Photographs 17-550-37-13 and 17-550-37-14 show some of the exposure in the coulee. At the eastern portion of the site, most of the river bank is covered by colluvium, however, one resistant near-horizontal sandstone bed could be traced for about 100 m (see Photograph 17-550-37-11). The amount of rock exposure increases towards the western edge of the site, where a large sandstone channel was observed (see Photograph 17-550-37-13). This sandstone unit is weathered, locally cross-bedded, contains sub-horizontal bedding planes and occasional sub-vertical joints, and can be traced up and across the coulee immediately east of the mouth of Tennessee creek (see Photograph 17-550-37-14). Photographs 17-550-37-15 and 17-550-37-16 are views looking southwest and southeast along Dr. Greggs' hypothesized fault traces X and B respectively. No bedding offset was observed at this site.

Site 6

Site 6 is located about 3.8 km southwest of Bitango Bridge and just east of the secondary road northern extension of Highway 6. In his report, Dr. Greggs indicates that the intersection of his hypothesized Faults X and C occurs in this area. The site consists of a ridge trending approximately east-west with some bedrock exposure along its southern edge (see Photograph 17-550-37-17). The rock exposure consists of flaggy, weathered sandstone containing sub-vertical joints which are open to 5 cm. The top of this ridge allows an excellent view to the northwest and northeast along Greggs' postulated fault traces X and C. No obvious regional lineaments could be ascertained from this viewpoint.

Site 7

Site 7 is located about 5 km downstream from the dam site where Dr. Greggs indicates that his hypothesized Fault A intersects the Oldman River. Bedrock exposure is plentiful along both sides of the river at this location and consists of channel facies sandstones which are weathered, flaggy in the upper few metres, locally cross-bedded and sub-vertically jointed (see Photographs 17-550-37-18 ad 17-550-37-19).

Site 8

Site 8 is located about 2 km downstream from the dam centreline where Dr. Greggs postulated Fault B crosses the Oldman River. Photograph 17-550-37-20 shows the extent of rock exposure at this location. Bedding planes can be traced across the full extent of this outcrop without any substantial offset. A few sub-vertical joints can be seen cross-cutting the bedding planes.

Site 9

Site 9 is located at the outlet portal excavation within the Oldman River Dam site, itself. Dr. Greggs indicates that his hypothesized Fault B and Fault Y intersect in this location. The rock exposed during excavation of the outlet portal was mapped in considerable detail by Mr. H. Hartmaier, P.Eng. and Mr. S. Bean, P.Eng. during 1987 and 1988. The results of this mapping indicate extensive horizontal continuity of the beds in this area.

Site 10

Site 10 is located just north of Summerview along the trace of Dr. Greggs' hypothesized Fault Y. Access permission could not be obtained from the landowner at this site. However, some rock exposure was evident and Photograph 17-550-37-21 is a view from the road looking northeast along the postulated trace of Fault Y.

Site 11

Site 11 is located just southwest of the confluence of the Castle and Oldman Rivers where Dr. Greggs' hypothesized Fault C intersects the Castle River. Extensive rock exposure along the northwest side of the Castle River valley is present at this location (see Photograph 17-550-37-22). The exposure consists of interbedded sub-horizontal sandstone, siltstone, and claystone units. The exposed siltstone and claystone layers are often nuggetted, weathered, contain randomly oriented slickensides, and are covered by a thin veneer of colluvium. The more resistant sandstone units form prominent near-vertical bluffs, containing sub-vertical joints. Some of these bedded sandstones can be traced for about 100 metres without any appreciable bedding offset. A little further downstream, a sandstone channel truncates some of the near horizontal beds. A brief inspection of rock exposures along this stretch of the Castle River yielded no evidence of offset beds, shear zones or fault gouge.

Site 12

Site 12 is located about 3 km west and about 0.7 km north of the Pincher Creek Airport where Dr. Greggs has inferred that his hypothesized Fault X intersects the Castle River. This site lies very close to the edge of the disturbed belt, marking the boundary between the Alberta Plain and the Rocky Mountain Foothills physiographic regions (UMA/Acres Report, November 1985).

A large rock exposure along the north and east sides of the Castle River was observed and is shown in Photographs 17-550-37-23 to 17-550-37-28. The exposure consists of interbedded clastic rocks dipping to the northeast from 10 to 25 degrees. Photograph 17-550-37-24 appears to show a possible angular unconformity, where the northeasterly dipping beds are truncated by some sub-horizontal beds just below the rock/overburden contact. Photograph 17-550-37-26 shows some gouge along some bedding contacts.

A brief inspection of this rock exposure yielded no evidence of any substantial near vertical bedding offset, however, much of the valley slope to the west is covered by colluvium (see Photograph 17-550-37-28).

Site 13

Site 13 is located about 6.5 km north of Cowley and about 1.8 km west of Secondary Road 510 where Dr. Greggs shows his hypothesized Fault C intersecting the Oldman River. Some rock exposure was observed along the west side of the river and it is shown in Photograph 17-550-37-29. At the south end of the site, the exposure consisted of sandstone just above river level. This sandstone was only slightly weathered and contained undulating shallow angle bedding planes. Further to the north, a sandstone bluff was observed which was weathered, flaggy and jointed. Much of the river valley slope was covered by colluvium which made it difficult to trace the continuity of beds.

Site 14

Site 14 is located about 2.2 km northeast of Pincher Station where Dr. Greggs indicates that his hypothesized Faults Y and C intersect. No rock outcrop was observed in this vicinity.

Site 15

Site 15 is located downstream of Bitango Bridge along the Oldman River where Dr. Greggs shows his hypothesized Fault B. During a brief walk along this 3 km stretch of river, numerous rock exposures were observed. Most of the exposures consisted of near vertical sandstone bluffs, which were weathered, sub-vertically jointed, and contained sub-horizontal bedding planes, some of which could be traced for tens of metres. No bedding offset, slickensides or fault gouge was observed.

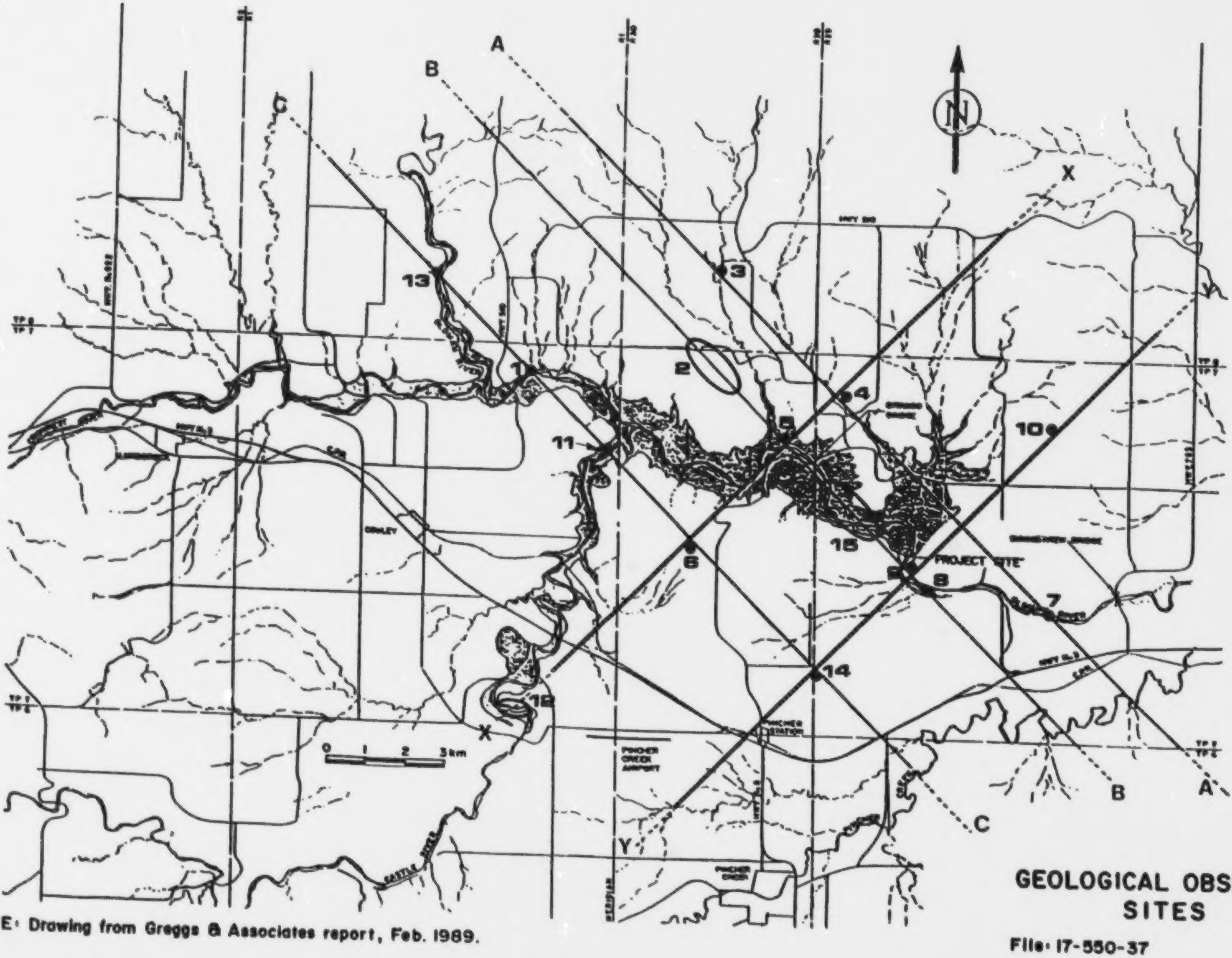
TABLE B1

SUMMARY OF OBSERVED GEOLOGICAL FEATURES

Site	Approximate Total Linear Extent of Rock Exposures	Rock Units Observed(1)	Approximate Traced Linear Continuity of Beds	Jointing Observed	Typical Joint Apertures(2)	Bedding Offset Observed	Slickensides Observed	Gouge Observed
1	700m	SS, MS, CS	100m	Sub-Vertical	0-5cm (6)	None	Within CS(3)	None
2	300m	SS	30m	Sub-Vertical	0-10cm	None	None	None
3	No Outcrop Observ.							
4	50m	SS	10m	Sub-Vertical	0-5cm	None	None	None
5	500m	SS, MS, CS	100m	Sub-Vertical	0-10cm	None	None(4)	None
6	100m	SS	10m	Sub-Vertical	0-5cm	None	None	None
7	400m	SS	100m	Sub-Vertical	0-5cm	None	None	None
8	150m	SS	150m	Sub-Vertical	-	None	None	None
9	200m	SS, MS, CS	200m	Sub-Vertical	0-3cm	None	Within CS(3)	None
10	Not Accessible							
11	300m	SS, MS, CS	100m	Sub-Vertical	0-5cm	None	Within CS(3)	None
12	300m	SS, MS, CS	75m	Sub-Vertical	0-2cm	None	None(4)	Along Contacts(5)
13	75m	SS	30m	Sub-Vertical	0-5cm	None	None	None
14	No Outcrop Observ.							
15	500m	SS	50m	Sub-Vertical	0-10cm	None	None	None

NOTES:

1. Rock unit abbreviations: SS - sandstone, MS - siltstone, CS - claystone
2. These joint apertures were measured within weathered sandstone units.
3. These slickensides were observed only within sub-horizontal claystone units and appeared to be randomly oriented.
4. Although no slickensides were observed at these sites, a more thorough examination of the mudrock units may reveal some slickensides.
5. Gouge was observed along some bedding contacts.
6. One joint aperture of about 30 cm was observed. This appeared to be associated with displacement of a rock wedge.


A
B
C
X
Y
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
PROJECT SITE
COWLEY
PINCHER CREEK AIRPORT
PINCHER STATION
PINCHER CREEK
CASTLE RIVER
0 1 2 3km

NOTE: Drawing from Greggs & Associates report, Feb. 1989.

GEOLOGICAL OBSERVATION SITES

File: 17-550-37

FIGURE B1

REFERENCES

Greggs and Associates, Preliminary Evaluation of the Bedrock Structure - Oldman River Dam Site Area, Southern Alberta, Report prepared for Friends of the Oldman River, February, 1989.

UMA/Acres, Oldman River Dam Preliminary Engineering Report, Appendix D, Foundation Exploration, Volume 1, Site Geology, Report prepared by Thurber Consultants Ltd., November, 1985.

APPENDIX B1

Photographs

Photo 17-550-37-1 Site #1 - Outcrop on north side of Oldman River about 0.6 km. downstream of Secondary Road 510 bridge.

Photo 17-550-37-2 Site #1 - Outcrop on north side of Oldman River about 1.1 km downstream of Secondary Road 510 bridge.

Photo 17-550-37-3 Site #1 - Outcrop on south side of Oldman River about 1.8 km. downstream of Secondary Road 510 bridge.

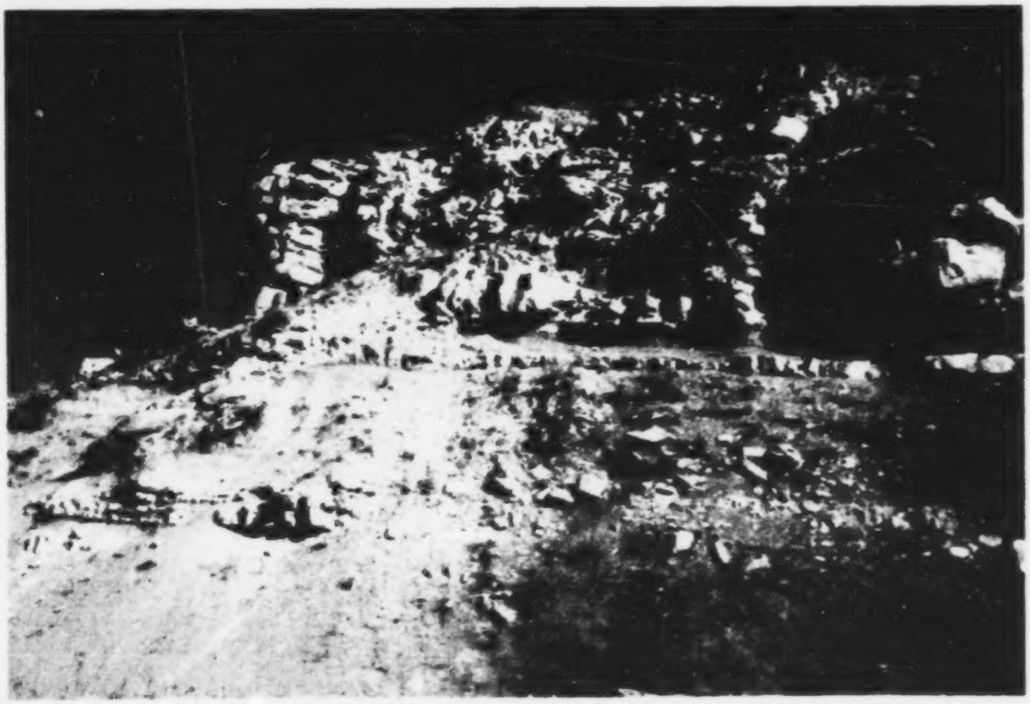


Photo 17-550-37-4 Site #1 - Outcrop on north side of Oldman River showing sandstone bluffs overlaying sub-horizontal mudrock units which are partially covered by colluvium.

Photo 17-550-37-5 Site #1 - View looking north into a coulee from the Oldman River approximately 1.0 km. downstream from the Secondary Road 510 bridge.

Photo 17-550-37-6 Site #1 - View looking north east at sandstone exposure about 0.6 km. douwnstream of Secondary Raod 510 bridge. Note: Enlarged joint open approx. 30cm. near the centre of the photo. This may be the same location as Plate B in the Greggs and Associates Report.

Photo 17-550-37-7 Site #2 - View looking north west at sandstone outcrop along the trace of Dr. Greggs' Fault B.

Photo 17-550-37-8 Site #2 - View looking north west at sandstone outcrop along the trace of Dr. Greggs' Fault B. This location is approximately 1.5 km. north west of the location in photo 17-550-37-7 above.

Photo 17-550-37-9 Site #3 - View looking south down Tennessee Creek from Secondary Road 510.

Photo 17-550-37-10 Site #4 - View of sandstone exposure looking north east.

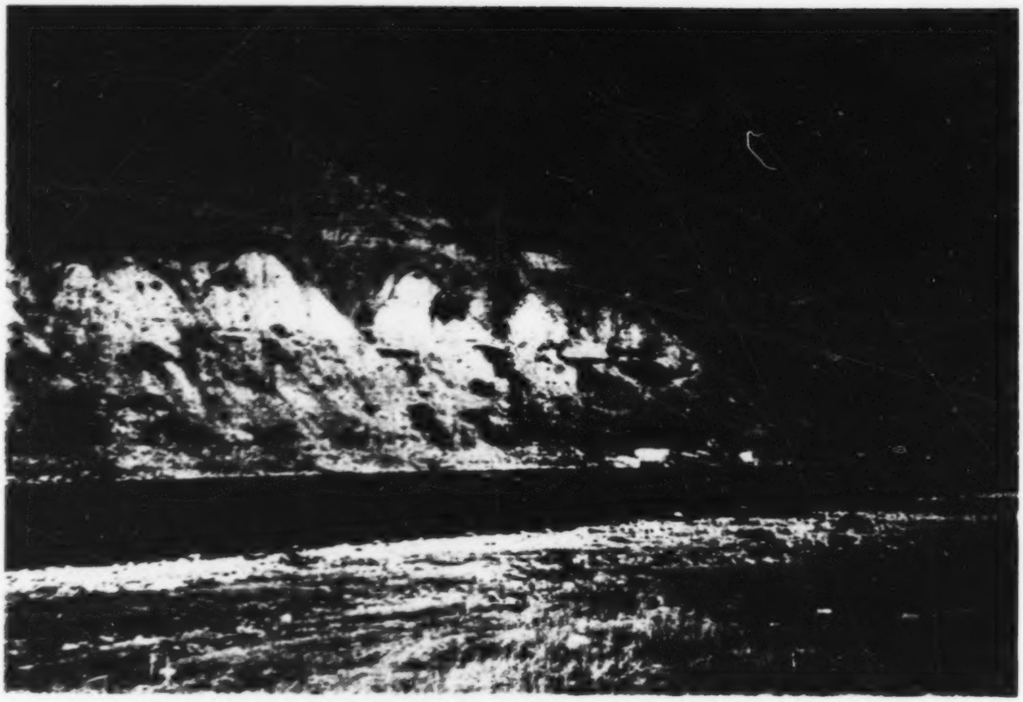


Photo 17-55-37-11 Site #5 - View looking north east at rock exposures along north side of the Oldman River. Note: Sub-horizontal sandstone bed.

Photo 17-550-37-12 Site #5 - View looking north west at rock exposures along north side of the Oldman River.

Photo 17-550-37-13 Site #5 - View looking south west at channel sandstone exposure in coulee which lies immediately east of the mouth of Tennessee Creek.

Photo 17-55037-14 Site #5 - View looking north east up coulee mentioned above. Note: Sandstone channel outcropping on both sides.

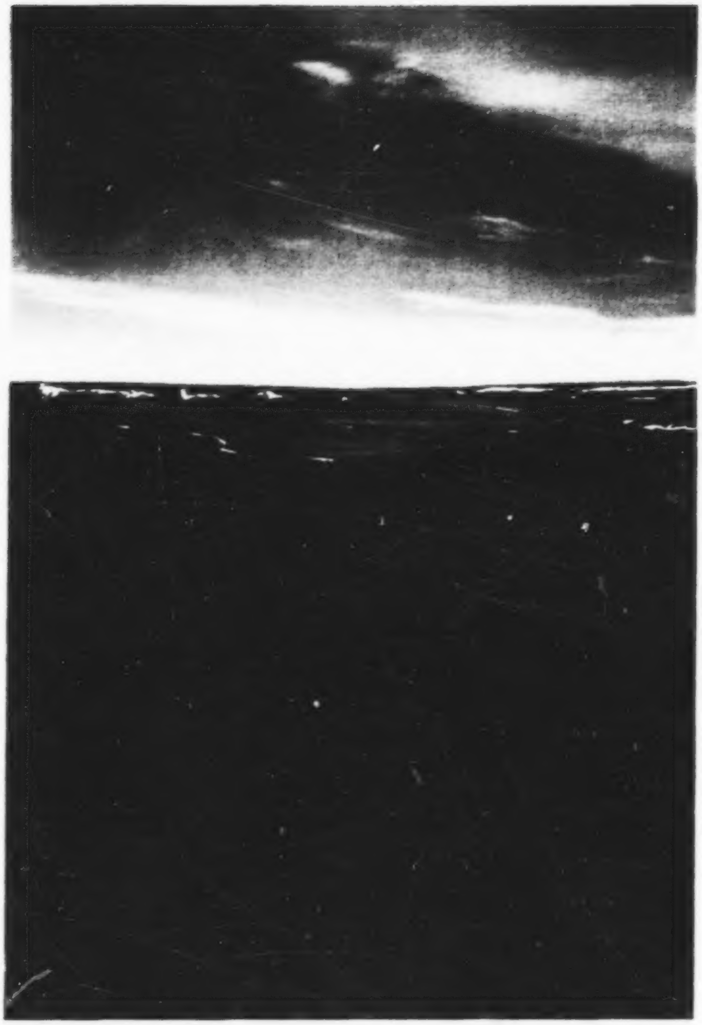


Photo 17-550-37-15 Site #5 - View looking south west along the trace of Dr. Greggs' hypothesized Fault X.

Photo 17-550-37-16 Site #5 - View looking south east along the trace of Dr. Greggs' hypothesized Fault B.

Photo 17-550-37-17 Site #6 - View looking north at rock exposure along ridge.

Photo 17-55037-18 Site #7 - View looking west at rock exposure along the south side of the Oldman River.

Photo 17-550-37-19 Site #7 - View looking north west at rock exposure along the north side of the Oldman River.

Photo 17-550-37-20 Site #8 - View looking south east at rock exposure along the south side of the Oldman River.

Photo 17-550-37-21 Site #10 - View looking north east along the trace of Dr. Greggs' hypothesized Fault Y.

Photo 17-550-37-22 Site #11 - View looking north east at the bedrock exposure along the north west side of the Castle River Valley.

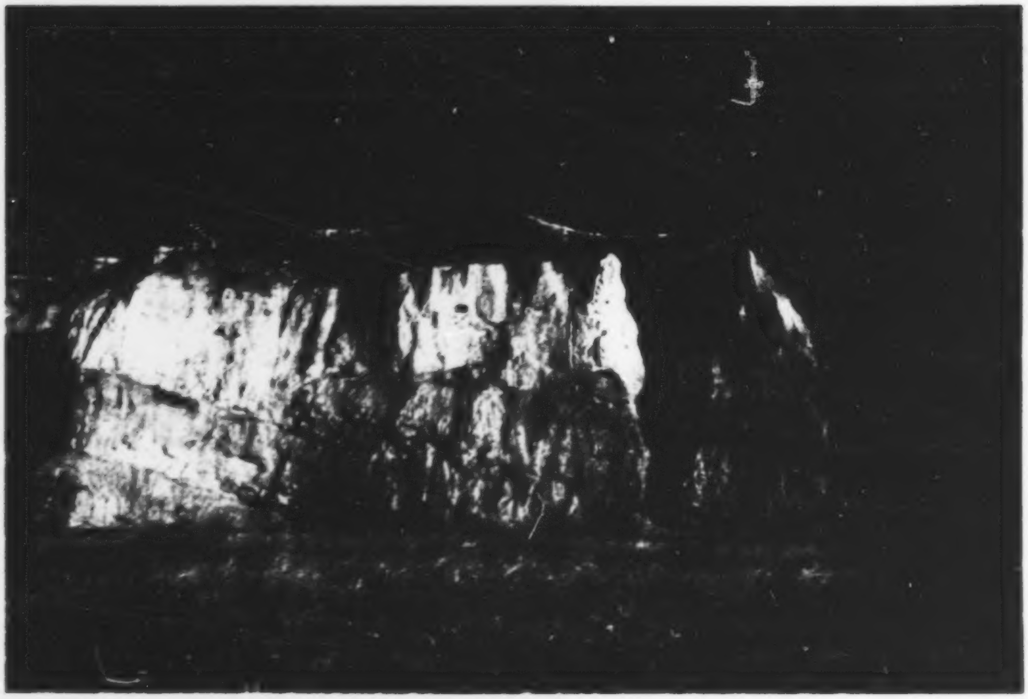


Photo 17-550-37-23 Site #12 - View looking north at rock exposure. Note: Beds dipping north east about 15 degrees and continuous gravel terrace material at top.

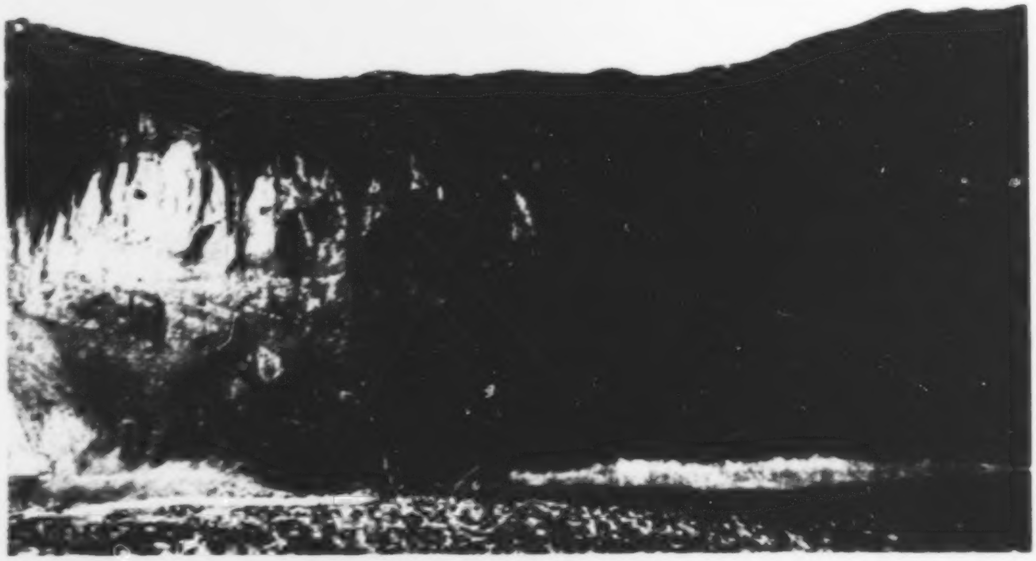


Photo 17-550-37-24 Site #12 - View looking north at rock exposure. Note: Possible angular unconformity just below rock - overburden contact.

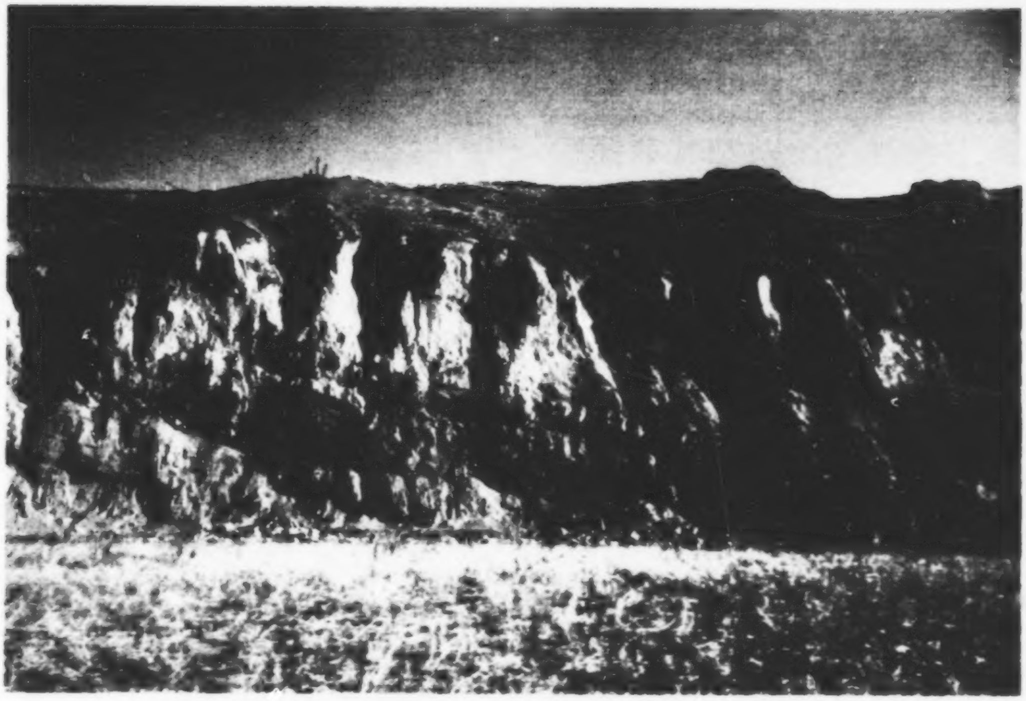


Photo 17-550-37-25 Site #12 - View looking north at rock exposure.
Note: Beds dipping to the north east at about 15 degrees.

Photo 17-550-37-26 Site #12 - View looking north at rock exposure next to the Castle River. Note: Dipping beds and open bedding plane contacts containing gouge and showing signs of interbedding slip.

Photo 17-550-37-27   Site #12 - View looking north east at rock exposure.

Photo 17-550-37-28   Site #12 - View looking north west at colluvium covered slopes.

Photo 17-550-37-29   Site #13 - View looking north west at rock exposure along the west side of the Oldman River.

APPENDIX B2

Follow-up Visit to Geological Site 1.

INTER OFFICE MEMO UMA Engineering Ltd.

TO D.B. Chalcroft/B.L. Baggott

FROM H.H. Hartmaier

RE Oldman River Dam Project
Follow up Visit to Geological
Observation Site #1

DATE
June 12, 1989

OUR FILE NO
2496-031-00-G416-1.2.1
2496-031-00-G416-1.30

As requested on June 12, 1989 a follow up visit was made to Geological Observation Site #1 as referenced in Figure 1 of "Site Observations Search for Evidence for Faults Hypothesized by Dr. Greggs" by Thurber Consultants. This report is found as Appendix B in the report prepared by UMA/Acres entitled "Oldman River Dam Review of Greggs and Associates Report to Friends of the Oldman River dated February 1989."

The purpose of the site visit was to obtain further details on the exposure described as Site 1 in the Thurber report.

The Thurber report, (Pg 2) states that "One enlarged joint system was observed which involved a wedge of rock being displaced about 30 cm".

The photographs of the site is given as Photo #17-550-37-6 in the Thurber report and appears to show the same outcrop as Photo B in the Greggs report.

Dr. Greggs' captions his photo B as "Enlarged joint system in sandstone unit of Porcupine Hills Formation and fault location just east (downstream) from locality in plate A.

Since this is the only location where Dr. Greggs has mentioned actually seeing a fault, it was worth re-evaluating the descriptions of the site.

Based on the most recent site visit the feature shown in both the Thurber report and the Greggs report is a slumped block of sandstone that has moved away from the bedrock cliff as a result of mechanical weathering action.

On the left side of the block (facing outcrop) a joint dipping at 80° in a 273° dip direction and is filled with about 30 cm of overburden.

Further to the left (upstream) of this feature two joints were noted in the sandstone face of the outcrop which showed about 50 mm of dip slip offset and about 150 mm of apparent left lateral strike slip offset. The joints are oriented - (dip/dip direction)

75/254
60/248

Upon further investigation it was found that the outcrop containing the joints also appears to have been detached from the main outcrop by a subvertical joint plane about 0.5 m back from the face oriented at 80/348.

Also, the joints showing the apparent offset did not continue upwards, in fact one was found to terminate against a sub-horizontal bedding plane with no offset.

In conclusion the near surface sandstone blocks in this area appear to be disturbed by weathering action and possibly slumped due to erosion and undercutting of less resistant rock units.

Local displacements such as these are expected to be found elsewhere along the river bank bedrock exposures. However they are not of tectonic origin as implied by Dr. Greggs.

H.H. Hartmaier, P.Eng.
Resident Engineering Geologist
Oldman River Dam Project

HHH/sai